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CHARACTERISTICS OF HY-180 AND Ti-100
FOR WELDED HIGH STRENGTH STRUCTURES

National Materials Advisory Board (NAS-NAE)
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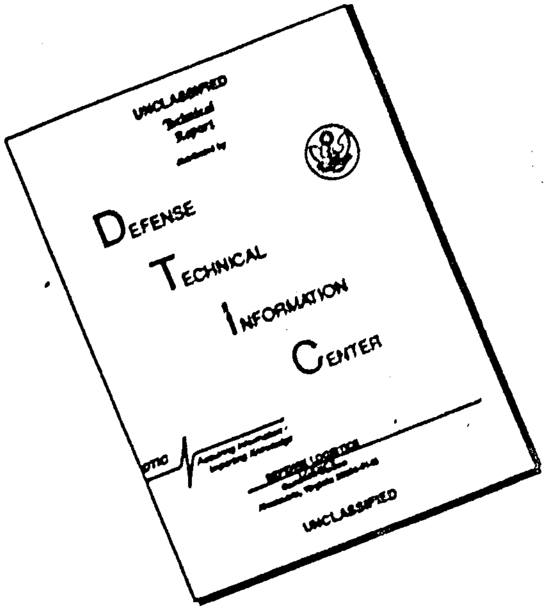

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A general review of the problems and potential of the various welding processes is included and those processes that show greatest promise and should be further developed are identified. The available information on the mechanical properties of state-of-the-art welds (made for the most part under laboratory conditions) also is discussed.

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CHARACTERISTICS OF HY-180 AND Ti-100 FOR WELDED HIGH STRENGTH STRUCTURES

REPORT OF

AD HOC COMMITTEE ON WELDING HIGH-STRENGTH STRUCTURES

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council
National Academy of Sciences-National Academy of Engineering

14

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ABSTRACT

The present state of the art and future developments necessary for successful commercial application of high-strength materials in welded structures are reported.

The 10Ni-8Co-2Cr-1Mo steel and the Ti-6Al-2Cb-1Ta-0.8Mo titanium alloy were selected as candidate materials on the basis of their outstanding fracture-resistance characteristics and their roughly equivalent strength-to-weight ratios. The availability; chemical composition, physical, and mechanical properties; and heat treatment and metallurgical characteristics of both candidate materials are summarized.

A general review of the problems and potential of the various welding processes is included and those processes that show greatest promise and should be further developed are identified. The available information on the mechanical properties of state-of-the-art welds (made for the most part under laboratory conditions) also is discussed.

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CONTENTS

I. INTRODUCTION

The National Materials Advisory Board (NMAB) ad hoc Committee on Welding High-Strength Structures was assembled to assess the state-of-the-art and identify future developments necessary for successful commercial application of high-strength materials in welded structures. The Committee initially considered high-toughness materials that, on a yield strength-to-weight basis, were comparable in performance to the 10Ni-8Co-2Cr-1Mo steel developed by United States Steel Corporation.

Of the available iron-base alloys, the maraging steels were eliminated from consideration because of the relatively high susceptibility to stress corrosion of their weld heat-affected zone.[1] The dual-strengthened steels, such as 9Ni-4Co-1Mo-Al, were not considered since it had been reported that considerable development would be necessary before production-size heats could be melted.[1] The HP9-4-XX steels, particularly HP9-4-20, showed excellent promise for some applications at yield strength levels of 180 ksi and above; however, because 10Ni-8Co-2Cr-1Mo steel (with its lower carbon content) exhibits considerably higher fracture toughness, it was selected as the candidate iron-base alloy.

On a strength-to-weight ratio basis, titanium-base alloys (density ~4.48 g/cm^3) with yield strengths of 100 ksi or greater are comparable to 10Ni-8Co-2Cr-1Mo (density 7.89 g/cm^3) at 180 ksi. Of the commercially available titanium alloys, only Ti-6Al-2Cb-1Ta-0.8Mo (Ti-6-2-1-1) and Ti-6Al-4V are competitive with 10Ni-8Co-2Cr-1Mo steel on a strength-weight basis, while possessing adequate fracture toughness and resistance to stress corrosion. When these alloys are produced with the low levels of iron and oxygen necessary to provide the toughness required for fracture-safe design, they have the same offset tensile-yield strength and compressive yield strength; however, Ti-6Al-2Cb-1Ta-0.8Mo has better toughness in plate form, based upon dynamic tear properties. Therefore the Ti-6Al-2Cb-1Ta-0.8Mo titanium alloy with a minimum yield-strength of 100 ksi was chosen for comparison with the 10Ni-8Co-2Cr-1Mo steel.

In the interest of brevity 10Ni-8Co-2Cr-1Mo steel will be referred to as HY-180 steel and the Ti-6Al-2Cb-1Ta-0.8M titanium alloy will be referred to as Ti-100.

Applications considered include the fabrication by welding of airframe components, missile cases, armor, high-performance ships, heavy-lift helicopter components, pressure vessels, and heavy-section structures. In these applications, materials are loaded to a large fraction of their tensile yield strength because of the combined requirements of structural efficiency and economy.

Catastrophic failures of high-performance structures, sometimes involving loss of life, have demonstrated the necessity for fail-safe or safe-life design. With the fail-safe concept a structure's material and design are integrated so that a flaw can grow to readily detectable size without the occurrence of catastrophic failure. Safe-life design is based upon the concept that an existing flaw, assumed to be below the limits of detection through nondestructive evaluation (NDE), will not grow to critical size and cause catastrophic failure during the design life of the structure. Application of both fail-safe and safe-life concepts demand materials that have exceptionally high resistance to flaw or crack growth and to fracture.

One design approach being taken in aerospace structures is to avoid plane-strain conditions. For a given stress, in the absence of plane-strain conditions, critical size cracks propagate by stable tear rather than by unstable catastrophic growth. Plane-strain conditions are avoided by limiting the thickness of the material; structural elements requiring section thickness greater than the minimum for plane strain conditions are made by laminating thinner sections.

II. FRACTURE TOUGHNESS CONSIDERATIONS

Intensive research on fracture toughness conducted during the past 15 years has resulted in the development of new test procedures and methods for quantitative characterization of the behavior of high-strength materials.[2] Fracture-safe structures now can be constructed of relatively brittle ultra-high-strength materials (200-250 ksi yield strength) using designs based upon linear elastic analysis provided that exact knowledge of both the stress level and the flaw size is available for all locations in the structure. However, the tendency of relatively ductile materials, such as HY-180 and Ti-100, to form comparatively large plastic zones at crack tips makes valid fracture toughness measurements impossible unless extremely large and prohibitively expensive specimens are used.*

The classic Charpy V-notch test provides a reasonable correlation with plane strain fracture toughness for high-toughness steels. For applications of steels at the 180 ksi yield strength level a Charpy V-notch 32 °F (0 °C) shelf energy of 65 ft-lb or more has been established as a preliminary acceptance level.[3] On the other hand, no such correlation between Charpy V-notch behavior and plane strain fracture toughness has been found for titanium alloys.

The dynamic-tear (DT) test was developed at Naval Research Laboratory (NRL)[4,5] in order to characterize the fracture resistance of materials over the full span of fracture toughness from brittle to plastic levels. The results of this test correlate well with the standard fracture toughness (K_{Ic}) values for both steels (Figure 1) and titanium alloys (Figure 2).

The ratio analysis diagram (RAD), also developed at NRL,[6] provides a convenient graphical method for indexing the fracture resistance of materials in terms of the results of various tests for measuring fracture toughness. The RAD

* The ASTM recommends a minimum test specimen thickness, B, as indicated by the following expression for valid measurement of plane-strain fracture toughness.[2]

$$B(\text{inches}) \geq 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$$

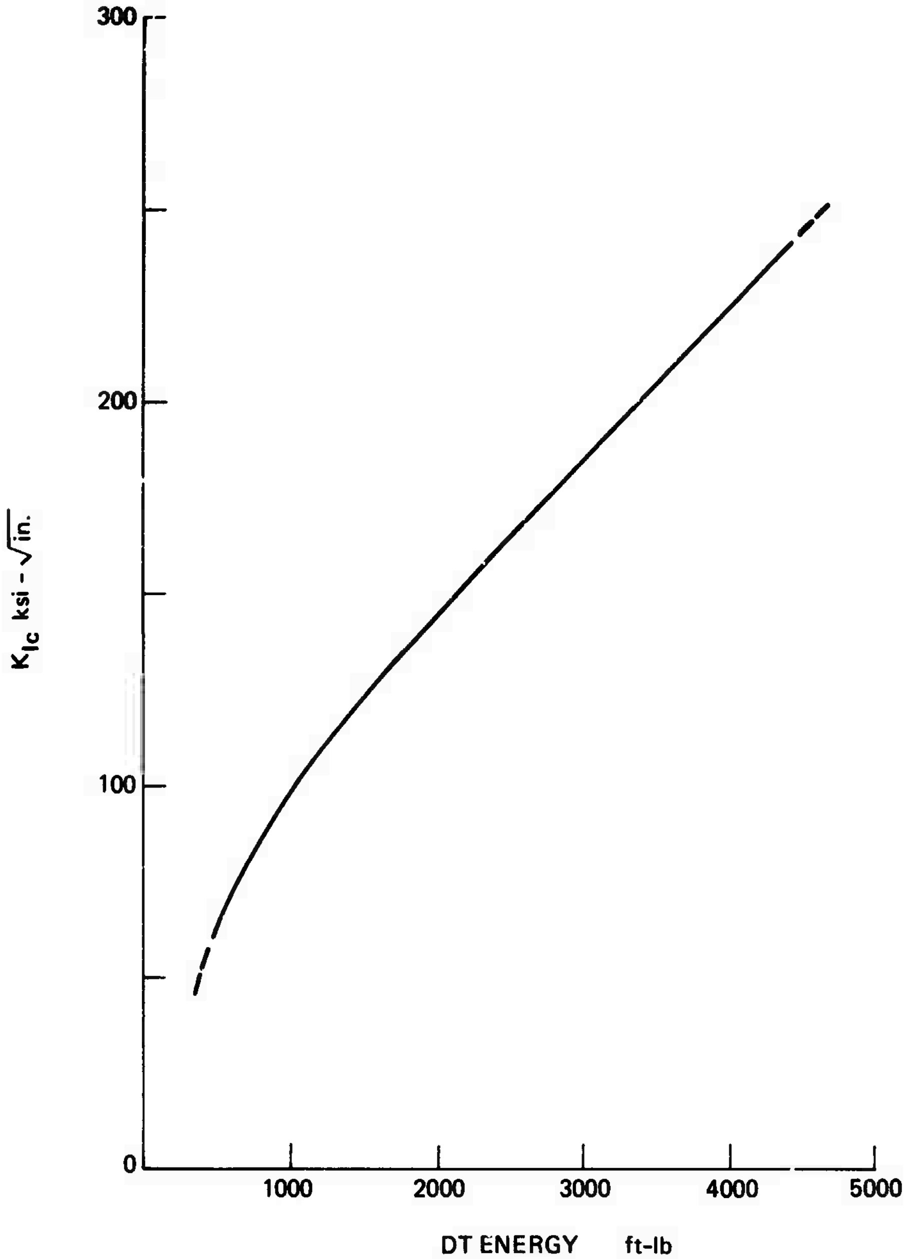


Figure 1 Correlation of dynamic-tear (DT) energy and K_{Ic} for 1-in. thick steels (Adapted from scales on RAD for 1-inch. steel plate in Reference 7).

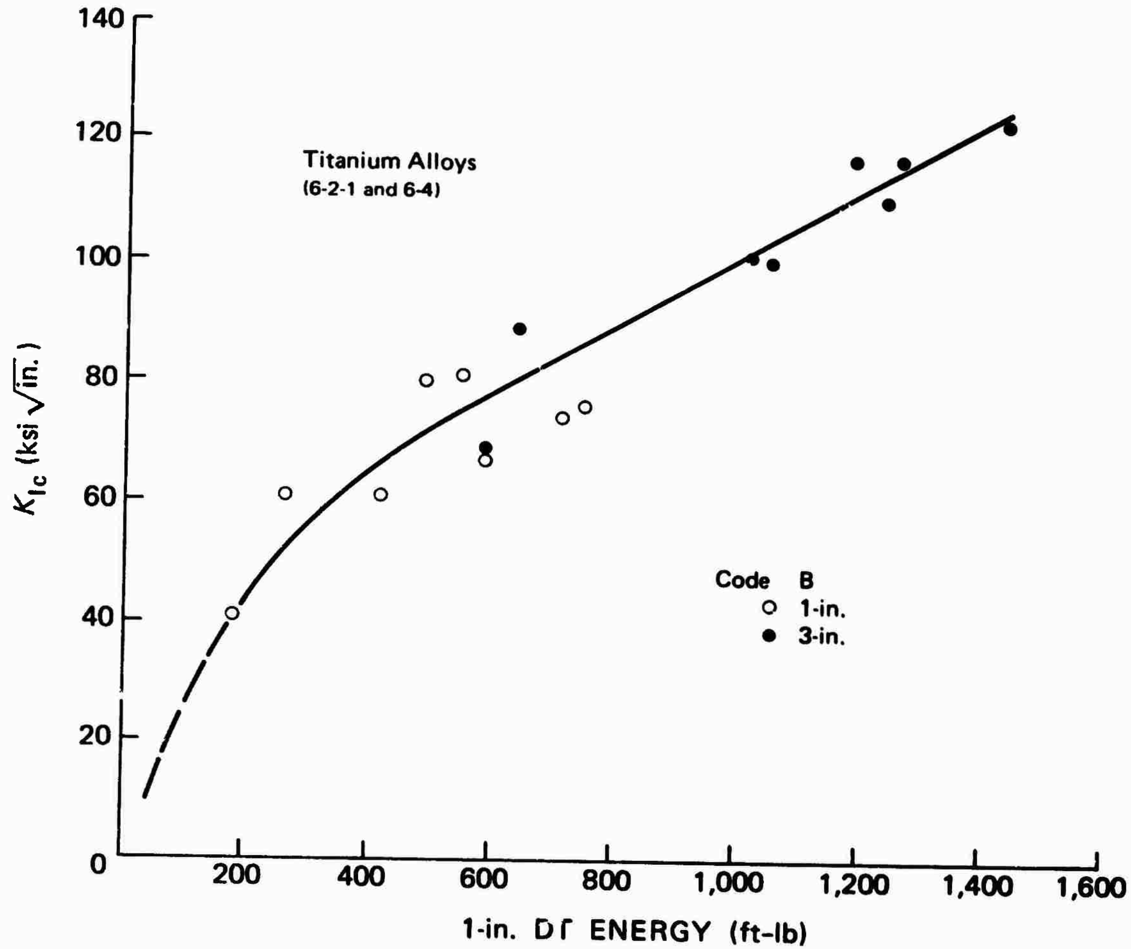


FIGURE 2 Experimental correlation of DT energy and K_{Ic} for 1-inch plates of titanium alloys with yield strengths from 105 to 140 ksi (from reference 9).

is zoned by lines representing selected values of the ratio K_{Ic}/σ_{ys}.*

For steels at the 180 ksi yield strength level, the DT energy corresponding to the $K_{Ic}/\sigma_{ys} = 1.0$ ratio line for 1-inch specimens is slightly below 3000 ft-lb. For titanium alloys at the 100 ksi yield strength level, the DT energy corresponding to $K_{Ic}/\sigma_{ys} = 1.0$ for 1-inch specimens is approximately 1000 ft-lbs. These DT energy values can be considered to represent the minimum values required to insure that fracture propagation can occur only by plastic instability in the presence of stresses above the nominal yield strengths of HY-180 and Ti-100, respectively.

The fracture toughness of both HY-180 and Ti-100 has been characterized by indexing on the appropriate RADS as shown in Figures 3 and 4 respectively. The loop labeled 10-8 0.12 in Figure 3 encloses the currently available DT test data for HY-180. This so-called "statistical expectancy box" indicates that DT energies range from 4000 to 8000 ft-lb for yield strengths ranging from slightly over 190 ksi to about 170 ksi. The dashed loop in Figure 4 presents similar information for Ti-100. The observed DT energies range from 1400 to 2500 ft-lbs for yield strengths ranging from slightly below 120 ksi to about 95 ksi. Thus it appears that, if properly produced, both candidate materials are capable of meeting the desired fracture toughness requirements. However, the data are based on

* Although formal analytical relationships for critical flaw sizes involve K_{Ic}/σ_{ys}, the linear ratio values are indicative of a specific level of fracture resistance.[6,7,8]

- If a material indexes below and to the right of the 0.5 ratio line, plane strain fractures may be initiated and propagated from relatively minute defects (0.1 in. or less) at relatively low elastic stresses.
- If a material indexes above and to the left of the 1.0 ratio line, fracture initiation is no longer possible at elastic stress levels for flaws residing in sections up to 2.5 inches thick.
- If a material indexes between the 0.5 and 1.0 ratio lines mixed mode fracture occurs in sections ranging from 0.6 to 2.5 inches thick and critical flaw size may be calculated.

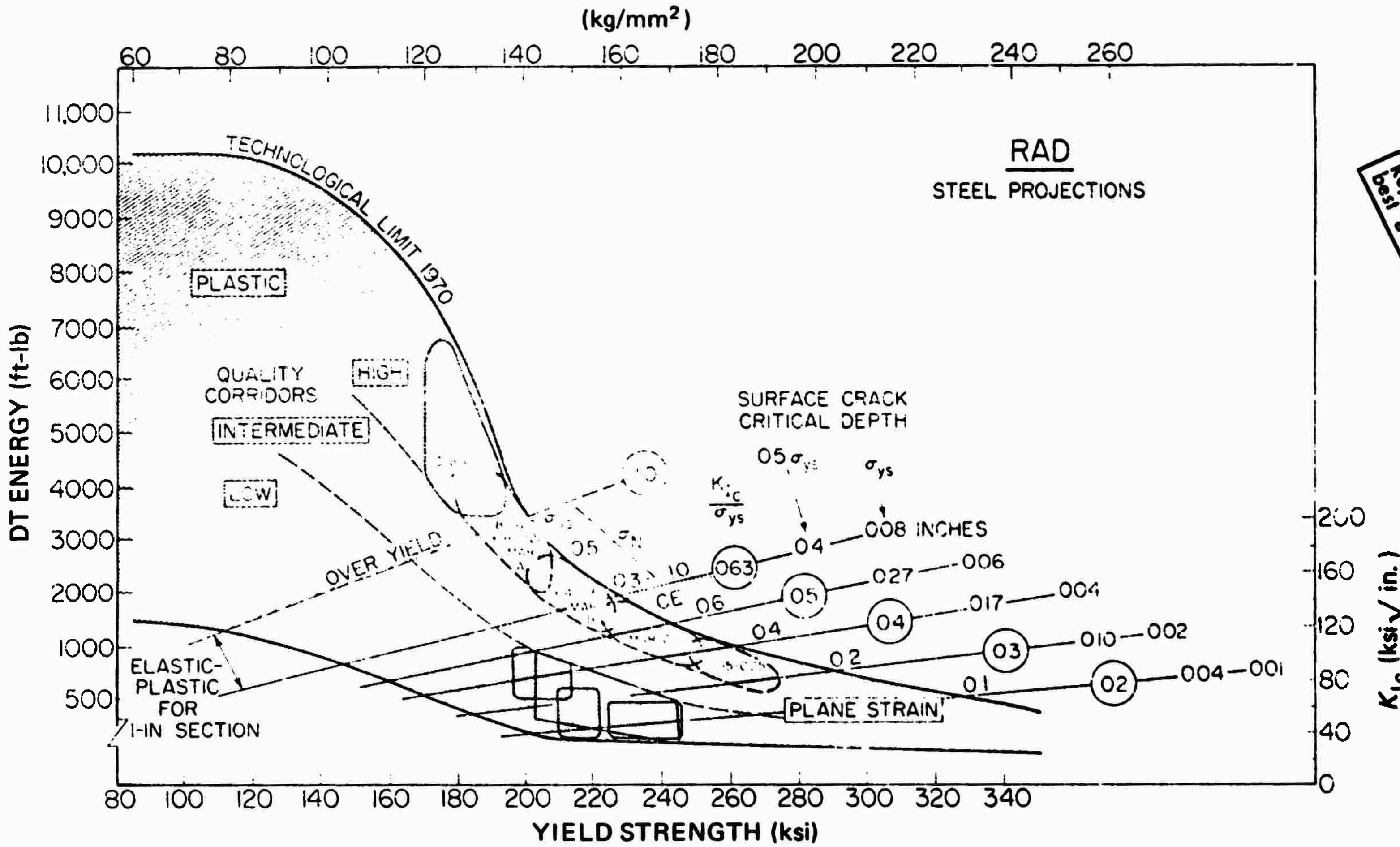


FIGURE 3 RAD zoning for the new, premium-quality, high-strength steels (from reference 8).

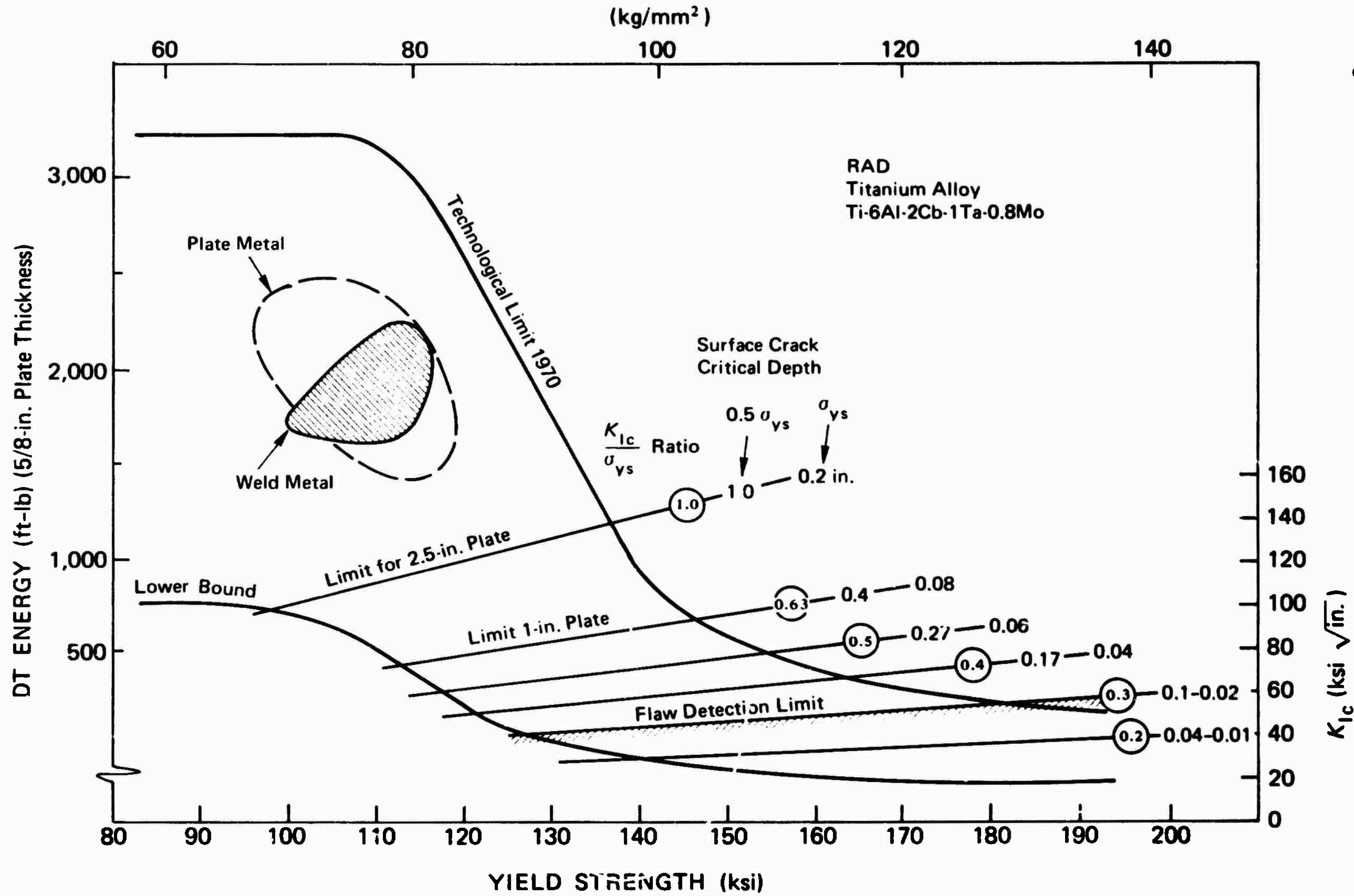


FIGURE 4 Comparison of weld-metal and base plate fracture properties of Ti-100 (from reference 9).

small experimental heats plus a limited number of production-size heats, and since metal processing and cleanliness have been shown to have a great influence on fracture toughness,[7] tests on additional production-size heats are needed to establish reliable, practical boundaries for the statistical expectancy boxes for both candidate alloys.

III. CHARACTERISTICS OF CANDIDATE BASE MATERIALS

A. HY-180 STEEL

1. AVAILABILITY

Both mill-annealed and heat-treated HY-180 steel can be provided in a variety of forms and sizes. Although the availability of a specific combination of form, size, and condition would have to be determined by consultation with the producer, the following ranges in forms and sizes generally are available:

a. Plate--maximum width of 120-inches, thickness of 3/8 to 8 inches, maximum length of 480 inches, maximum weight of 23,000 pounds.

b. Forgings--maximum weight of approximately 23,000 pounds.

c. Seamless tubes--diameters from 2-3/8 to 26 inches; wall sizes from 0.154 to 1.656 inches depending on diameter, lengths from 32 to 36 feet depending on size (special heat-treating facilities are required for diameters over 14 inches).

d. Extruded tubes--diameters from 6 to 20 inches, wall sizes from 3/8 to 4 inches, maximum length of 40 feet, maximum weight of 11,000 pounds.

e. Extruded shapes--Maximum cross-sectional area enclosed in a 21-1/2 inch circle, maximum length of 10 feet maximum weight of 11,000 pounds.

f. Bars--diameters from 3/8 to 9-1/2 inches, lengths, up to 35 feet (also available in squares, flats, hexagons, and other special shapes that can be produced on a bar mill).

2. COMPOSITION AND PROPERTIES OF HY-180 STEEL PLATE AND FILLER WIRE

Table 1 summarizes the composition limits for HY-180 plate and two typical HY-180 filler wires. Both minimum specified and typical mechanical properties for HY-180 steel are listed in Table 2, and Table 3 lists miscellaneous physical properties of HY-180 steel. Table 4 presents a summary of heat treatments.

TABLE 1 Chemical Composition of HY-180 Steel [10,40]

	Amount Percent	Filler Wire	
Element	Plate	Airco	U.S.S.
C	0.09-0.13	0.05	0.10
Mn	0.05-0.25	0.05 max.	0.05 max.
P	0.010 max.	0.010 max.	0.010 max.
S	0.006 max.	0.005 max.	0.005 max.
Si	0.15 max	0.05 max.	0.012
Ni	9.5-10.5	9.0	10.0
Cr	1.8-2.2	2.0	2.0
Mo	0.9-1.1	1.0	1.0
Co	7.5-8.5	12.0	6.0
Ti[a]	0.02 max.		
Al[a]	0.025 max.	0.005	0.025
N[a]	0.0075 max.	0.005 max.	0.005 max.
O	0.0025 max.	0.0025 max.	0.0025 max.
V			0.07

[a] As Residual

TABLE 2 Mechanical Properties of HY-180 Steel [10,11]

	Specified Minimum for Section (longitudinal & transverse)		Typical for Section (midthickness)	
Property	3/8 to 2 in.	2 to 4 in.	2 in.	4 in.
Ultimate Strength (ksi)	a	a	200	189
Yield Strength, 0.2% Offset (ksi)	180-195	175-190	185	178
Elongation in 2 in. (%)	15	15	17	18
Reduction of Area (%)	65	65	71	70
Charpy V-Notch Energy at 0 °F (ft-lb)	50[b]	a	90	75

[a] For information only.

[b] Average of three specimens.

TABLE 3 Miscellaneous Physical Properties of HY-180 Steel[11]

Property	Value
Modulus of Elasticity in Tension	27.7×10^6 psi, 190.9×10^9 N/m^2
Modulus of Elasticity in Compression	28.5×10^6 psi, 196.4×10^9 N/m^2
Shear Modulus of Elasticity	10.7×10^6 psi, 73.7×10^9 N/m^2
Poisson's Ratio	0.3
Coefficient of Linear Expansion	(80 - 1100 °F) 6.35×10^{-6} in./in./°F (27 - 593 °C) 11.43×10^{-6}cm/cm/°C
Density	(86 °F) 0.287 lb/in.^{3}, (30 °C) 7.95 g/cm^3,
Magnetic Properties	B_{sat} (flux density at saturation) - 18,500 gauss, 1.85 T H_{sat} (magnetizing force at saturation) - 400 oersteds, 31,830 A/m H_c (coercive force) (when B_{sat} is 15,000 gauss) - 20 oersteds, 1,590 A/m (estimated) Permeability (H max) - 272
Machinability	Use removal rates approximately 15% lower than those used for AISI 4140 steel at the same strength level.
Specific Heat	(32 °F) 0.100 Btu/lb/°F, (0.°C) 420 J/kg/°C
Electrical Resistivity	(32 °F) 127.5 microohm-in. (0°C) 50.2 microohm-cm.
Thermal Conductivity	(32°F) 128.3 Btu /sq.ft/in./°F/in (0°C) 18.5W/sq.m/°C

TABLE 4 Heat Treatments for HY-180 Steel [10, 11]

Treatment	Requirements
Normalize -	1650 °F ± 25 °F for 1 hour per inch of section (3 hours maximum), water quench.
Austenitize -	1500 °F ± 25 °F for 1 hour per inch of section (3 hours maximum), water quench.
Temper -	950 °F for 5 hours for sections through 1 inch thick. 950 °F for 10 hours for sections over 1 inch thick.
Soften -	1150 °F for 16 hours (31 R_c hardness).

3. TOUGHNESS OF HY-180 STEEL

The RAD for 1-inch 10Ni-8Co HY-180 plate (Figure 5) indicates DT energies ranging from 4,000 to 8,000 ft-lb depending upon heat and heat treatment variations. Figure 5 shows typical Charpy V-notch transition curves for both ½-inch plate and the quarter thickness location in 1-inch thick HY-180 plate. The nil ductility temperature of this steel is below -200 °F (-129 °C).

4. COMPOSITION AND PROPERTIES OF HY-180 CASTINGS

In a limited study of HY-180 castings conducted at the U.S. Steel Research Laboratory plate-type castings (Figure 6) were produced and evaluated. The best mechanical properties were observed in sound portions of castings from a vacuum-melted and air-cast heat of aluminum-deoxidized steel. The chemical composition of the castings and best mechanical properties observed in 1- and 4-inch-thick plate castings are shown in Table 5. The 45 ft-lb Charpy V-notch energy at 0 °F is reported to be somewhat lower than that associated with the fracture toughness $(K_{Ic}/\sigma_{ys})^{2}$* required to provide a ratio of 1.0 and thus provide leak before fracture failure in 3-inch plate. The yield strength values, 171 and 175 ksi, also were somewhat below the 180 ksi minimum desired.

5. METALLURGICAL CHARACTERISTICS OF HY-180 STEEL

a. Transformation and Tempering Characteristics

Figure 7 shows a tentative isothermal transformation diagram for HY-180 steel. The position of the bainite nose has been estimated to correspond to the dashed lines in Figure 7.

Figure 8 summarizes the effects of temperature on the tempering (or aging characteristics) of a typical heat of this steel. Figure 9 shows the effect of time of aging at 950 °F (510 °C) on the same mechanical properties but was prepared from tests conducted on a different heat of steel.

* Often approximated by (K_{Ic}/σ_{ys}) when the ratio is close to 1.0.

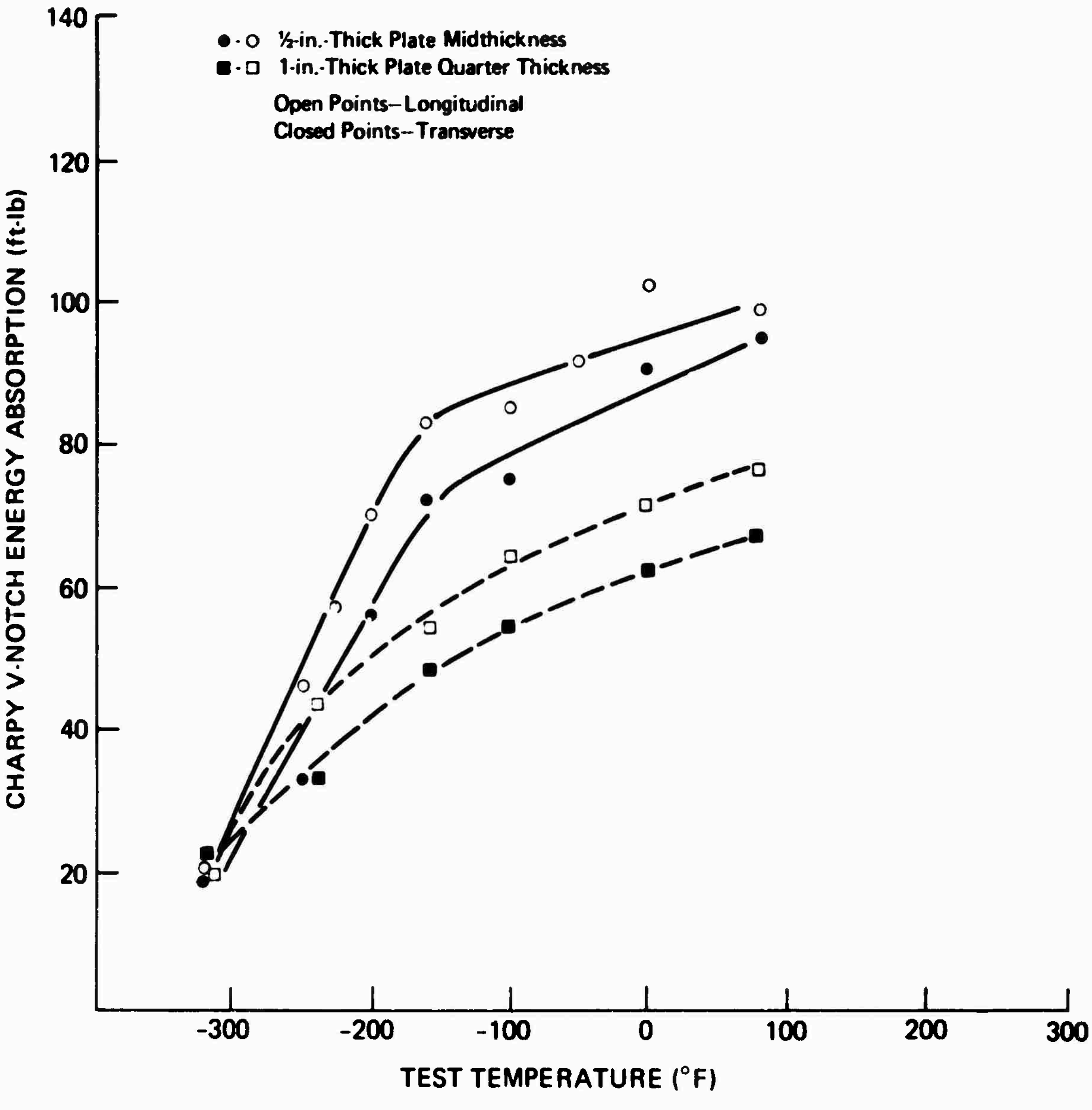
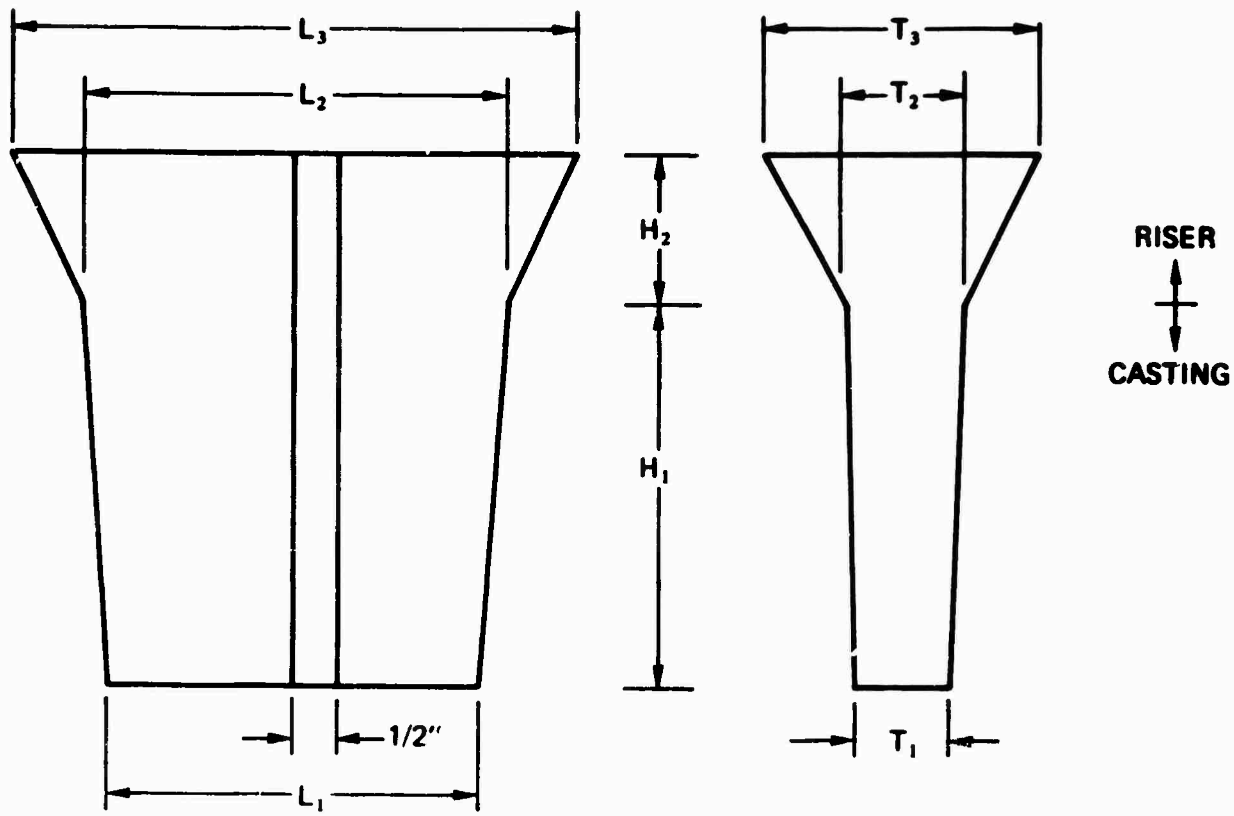


FIGURE 5 Charpy V-notch energy-absorption transition curves for $\frac{1}{2}$- and 1-inch-thick plates of VIM-VIR HY-180 steel.[12]



APPROXIMATE DIMENSIONS–INCHES

CASTING	L_1	L_2	L_3	T_1	T_2	T_3	H_1	H_2
SMALL	5 3/4	6 1/8	8 1/2	1	1 1/8	3	6	4
LARGE	11 1/2	12	13 1/2	4	4 1/4	6	11 1/2	5 3/8

FIGURE 6 Schematic drawing of HY-180 castings (from reference 13).

TABLE 5 Chemical Composition and Best Mechanical Properties Obtained from Vacuum Induction Melted Air-Cast (Aluminum-Deoxidized) HY-180 Steel [13]

Element/Property	Casting Thickness (in.) 1	4
Check Analysis (%)		
C	0.11	0.11
Mn	0.13	0.16
P	0.003	0.002
S	0.003	0.003
Si	0.04	0.08
Ni	10.3	10.1
Cr	1.99	1.95
Mo	1.08	0.95
Co	8.18	8.08
Al	0.004	0.006
N	0.002	0.002
O	0.011	0.022
Tensile Properties		
Yield strength, 0.2% offset (ksi)	171	175
Tensile Strength, (ksi)	187	191
Elongation in 1 in. (%)	13	16
Reduction of Area, (%)	41	60
Charpy V-Notch Impact Properties at 0 °F		
Energy absorption, (ft-lb)	36	45
Lateral expansion, (mils)	18	20

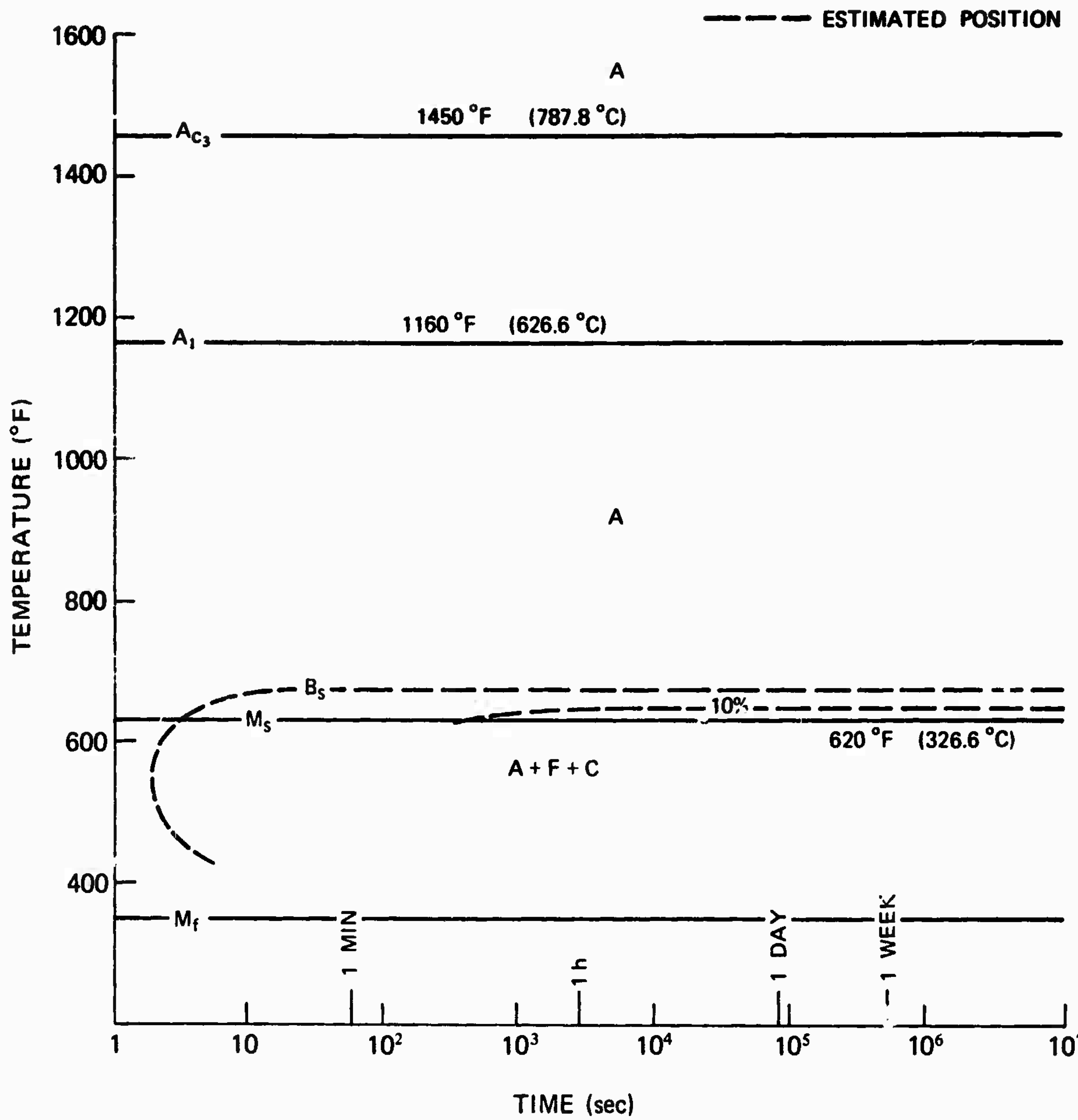


FIGURE 7 Tentative isothermal transformation diagram for 10Ni-8Co-2Cr-1Mo steel.[14]

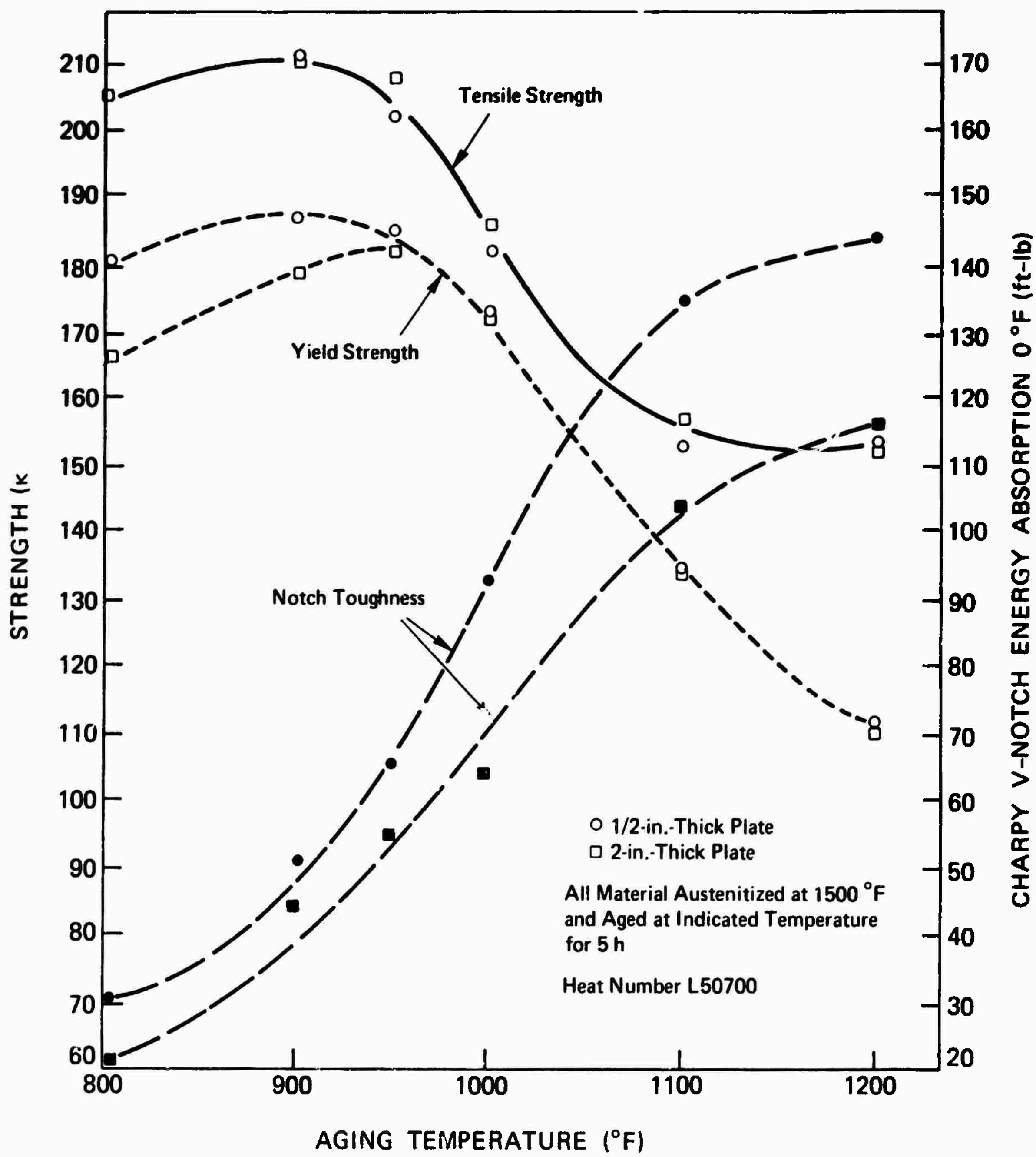


FIGURE 8 Effect of aging temperature on the longitudinal mechanical properties of HY-180 steel plates.[11]

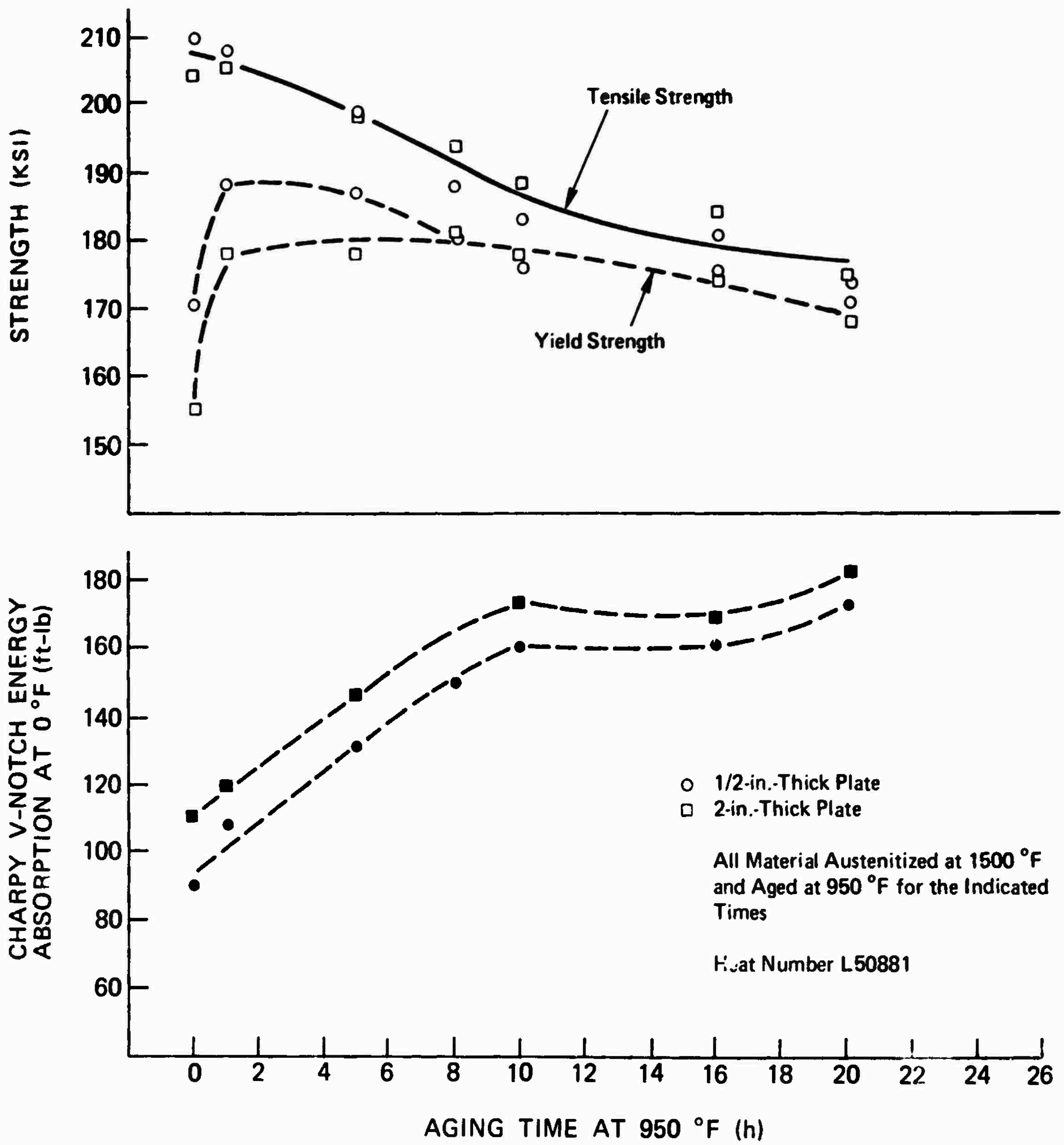


FIGURE 9 Effect of aging time at 950 °F on longitudinal midthickness mechanical properties of 10Ni-Cr-Mo-Co steel plates. 11

b. Effect of Residual Elements on Mechanical Properties

To exploit the full potential of the Ni-Cr-Mo-Co alloy-steel system, certain residual elements must be maintained at low levels, as is true of all high-yield-strength steel weldments. The pronounced effect of sulfur content on the shear-energy absorption of ultraservice steels was studied earlier in the HY-130 steel and in maraging steels, and sulfur was found to affect the HY-180 steel in a similar manner (Figure 10). Thus, the effect of sulfur on toughness appears to be quite general and the same shape curve is obtained regardless of steel type--it is merely displaced downward and toward lower sulfur contents as the strength of the steel is increased.

An extremely low level of oxygen is required to prevent the formation of oxide particles that would lower the toughness of the steel. Accordingly, the steel composition is purposely designed to be free of strong oxide formers. This permits the removal of oxygen to levels of less than 10 ppm during vacuum-arc remelting by a vacuum-carbon-deoxidation reaction.

Manganese and silicon commonly are added to steel for deoxidation, hot workability, etc. However, for the 10Ni-Cr-Mo-Co steel, significant benefits in toughness can be obtained if these elements are maintained at low levels. In particular, silicon appears to exert a strong deleterious effect on transition temperature (Figure11). It also appears from Figure 11 that, except for the low silicon heats at testing temperatures above 100 °F (35 °C) the 10-hour aging at 950 °F (510 °C) gave lower toughness than the 5-hour aging at 950 °F.

An interesting interaction between aluminum and nitrogen is illustrated in Figure 12. At low levels of aluminum, an increase in nitrogen decreases toughness only moderately; however, at a high aluminum content, a similar increase in nitrogen decreases toughness markedly. Thus it appears that when a low nitrogen level is maintained, aluminum or other strong nitride formers do not exert a significant effect on toughness.

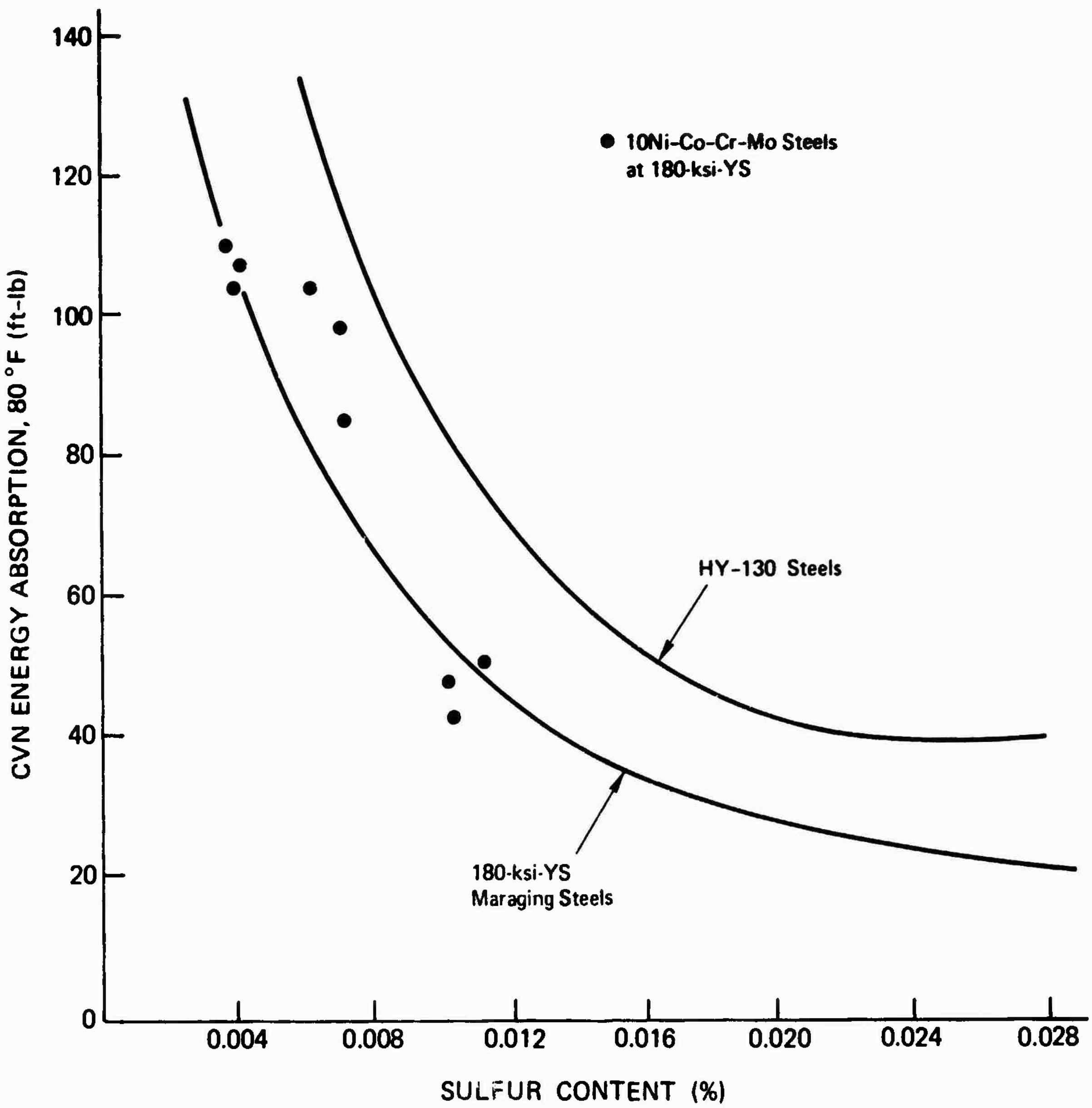


FIGURE 10 Effect of sulfur on low-residual high-strength steels (from reference 15).

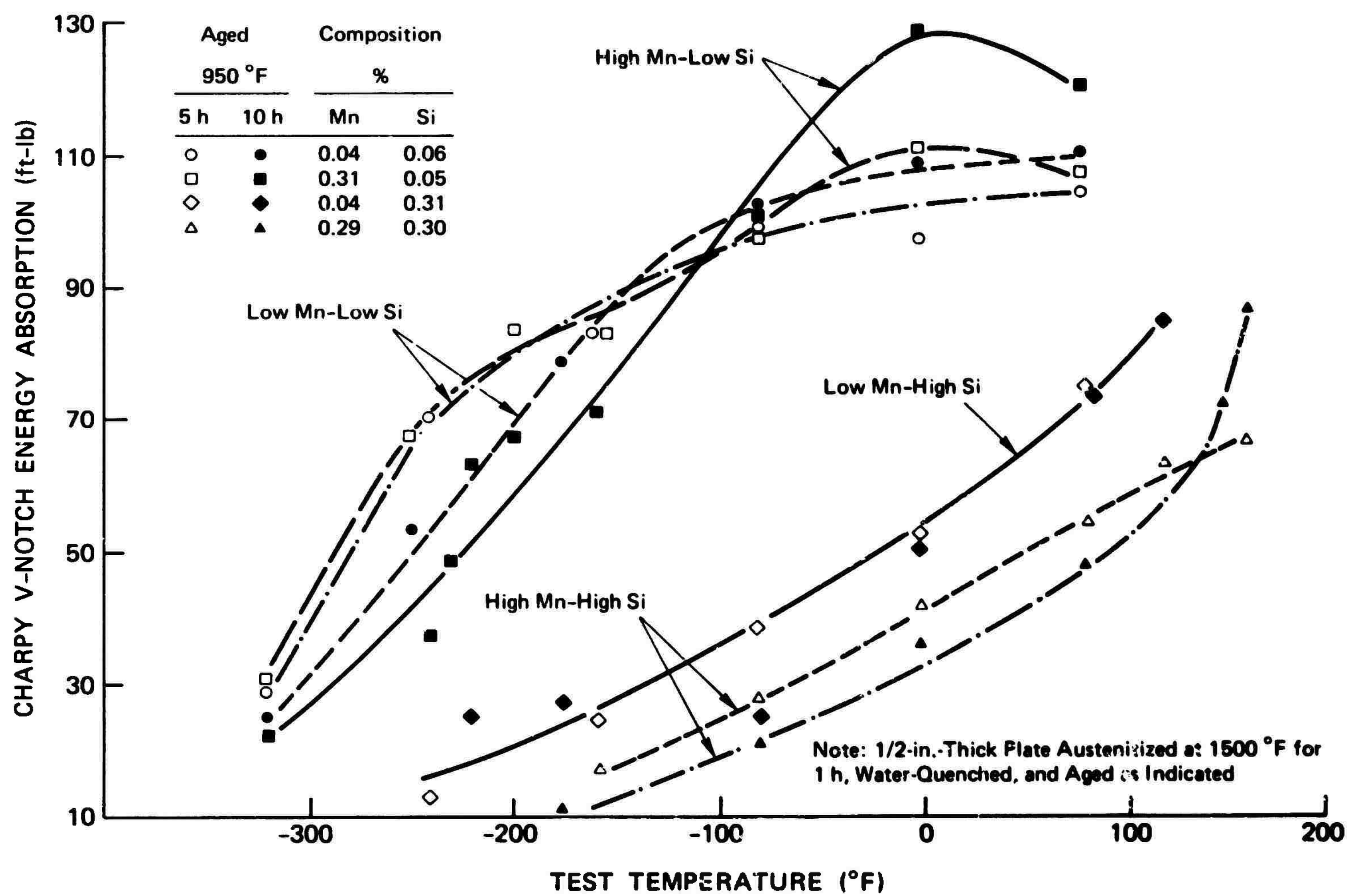


FIGURE 11 Effect of manganese and silicon content on Charpy V-notch energy absorption transition curves of 10Ni-8Co-2Cr-1Mo steel.[11]

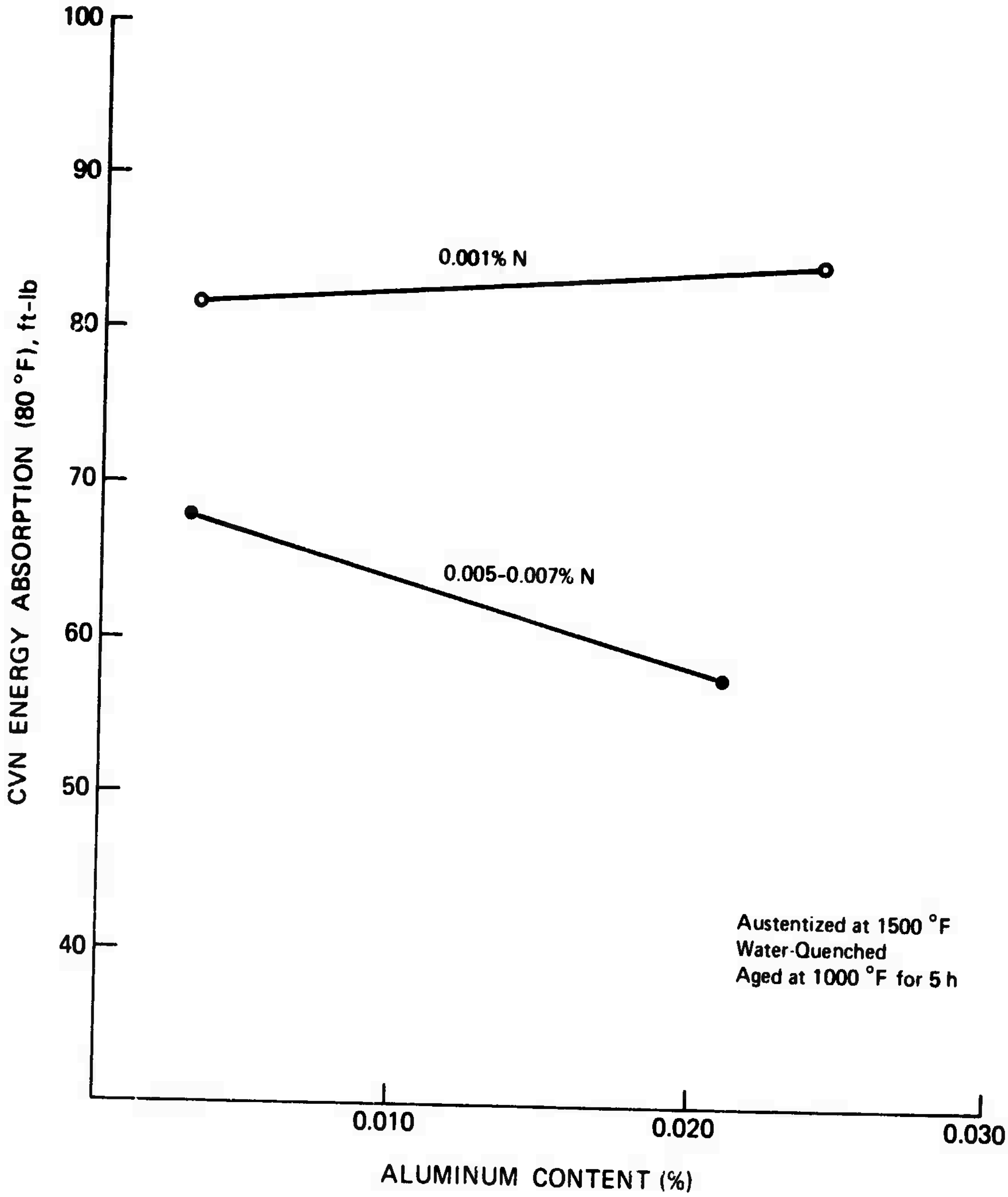


FIGURE 12 Effect of aluminum and nitrogen on the toughness of 10Ni-Cr-Mo-Co steel.[11]

Alloy steels generally are susceptible to temper embrittlement from the presence of a class of impurity elements (subversive elements) that includes antimony, arsenic, tin, and phosphorus. The embrittlement occurs when the steels are held or slowly cooled in the 1050 to 700 °F, (565.6 to 371 °C) range during or after tempering. To determine the susceptibility of HY-180 steel to this type of embrittlement, a series of each of the above-mentioned subversive elements were added singly, and the steels were subjected to a series of six different heat treatments.

No significant embrittlement, regardless of heat treatment, was exhibited when antimony was present in amounts less than 0.020 percent, when arsenic was present in amounts less than 0.047 percent, when tin was present in amounts less than 0.008 percent, or when phosphorus was present in amounts less than 0.17 percent. However, when present at the 0.075 percent level, antimony embrittled conventionally heat-treated HY-180 steel, and when present at their highest levels, antimony, tin, and phosphorus embrittled steels aged at 950 °F (510°C) for 20 hours. All the elements, when present at their highest levels, embrittled steels subjected to a program of step cooling with a 24-hour holding period at 900 °F (482 °C) and a 48-hour holding period at 875 and 850 °F (468.3 and 454.4 °C). The step-cooling treatment resulted in a yield-to-tensile strength ratio of about 0.99 for all steels, whether or not embrittlement was present. Thus, in considering elevated-temperature service or in establishing stress-relieving heat treatments, the possible effects of the thermal cycle on the yield-to-tensile strength ratio should be determined. Fractographic studies indicate that the embrittled steels fracture at prior-austenite grain boundaries, as is normally observed in temper-embrittled steels.

In the absence of subversive elements, HY-180 steel appears to be highly resistant to temper embrittlement. The levels of subversive elements normally present in the steel and the heat treatment normally performed on the steel are not expected to produce embrittlement of the type described above.

B. Ti-6Al-2Cb-1Ta-0.8Mo (Ti-100)

1. Availability

From the standpoint of rolling facilities Ti-100 is available in plate form with a maximum width of 200 inches and a maximum length of about 48 feet. However, the melting capacity of the only U.S. producer of Ti-100 limits the length of a 3-inch by 10-foot plate to 20 feet. While the melting capacity of the U.S. producer also limits weights to 15,000 pounds, titanium ingots as large as 25,000 pounds are known to have been produced in the United States.

2. Composition and Properties of Ti-100

Table 6 presents the composition limits for Ti-100 together with a typical analysis for heavy plate.

The mechanical properties of 1- and 2-½-inch-thick plates of Ti-100 are listed in Table 7. The heats were prepared by consumable arc melting at least twice. Properties are given for rolling from a temperature above the beta transus temperature (beta rolling) and below the beta transus temperature (alpha+ beta rolling). The two practices result in markedly different microstructures. Alpha + beta rolling was found to result in threshold values for stress corrosion (i.e., K_{Iscc} of about half that of beta rolled material) and therefore is considered undesirable. However, a significant variation in microstructure can be observed for beta rolled plates depending upon how much work is done after the temperature falls below the beta transus temperature. It would appear that microstructure influences the DT energy, but just how is not clear (Table 7). Efforts currently are in progress to clarify the relationship between processing schedules, microstructure, and DT energy.

Typical physical properties for Ti-100 alloy are compiled in Table 8.

3. Toughness of Ti-100

Charpy V-notch impact energy vs temperature for a 2.5-inch plate of Ti-100 is shown in Figure 13 and additional data for 1-inch plates are given in Table 9. Impact energy values are generally at high levels, 30 ft-lb or more at room temperature and 32 °F (0 °C), and 25 ft-lb or more at -80 °F, (-62 °C) except for the 1-inch plate of Heat No. 293708AB that had impact values of 19 ft-lb at 32 °F and 14 ft-lb at -80 °F (-62 °C). Annealing this as-rolled material above the beta transus temperature (i.e., 1910 °F (1043 °C)--1 hour--furnace cooled)

TABLE 6 Composition of Ti-100, Percent[16]

	Desired Aim[a]	Typical[a]
Al	5.5-6.5	6.0
Cb	1.5-2.5	2.0
Ta	0.5-1.5	1.0
Mo	0.5-1.0	0.8
Fe	0.15 max.	0.08
C	0.04 max.	0.02
N	0.012 max.	0.006
O	0.10 max.	0.08
H	0.008 max.	0.005

[a]For up to 3-inch plate.

TABLE 7 Summary of Properties of Plates of Ti-100 Produced

Material Code	Heat No.	Plate Thickness (in.)	Rolling Practice	Location	Specimen Direction	Properties YS (ksi)	Properties CVN (32°F) (ft-lb)	DT(RT)	Residual Elements, (%) Fe	C	N	O	H
EJO	292555	1	β		Long.	102	30		0.06	0.02	0.007	0.073	0.0060
					Trans.	101	29						
			β+A		Long.	100							
					Trans.								
EKK	292596	1	β		Long.	98	41		0.07	0.02	0.005	0.055	0.0039
					Trans.	101	30						
EJN	292596	2.5	β	Surface	Long.	97	27		0.07	0.02	0.006	0.067	0.0060
					Trans.	100	-						
				Midthk.	Long	96	26						
					Trans.	99	-						
EMC (W)	292596	1	β+ST		Long.	106	25	1420	0.07	0.02	0.005	0.055	0.0039
					Trans.	109	24	1360					
			β+STA		Long.	113	22						
					Trans.	115	21						
EMS	292596	2.5	β+ST	Surface	Long.	108	33		0.07	0.02	0.006	0.067	0.0060
					Trans.	105	30						
				Midthk	Long.	107	26						
					Trans.	105	29						
		2.5	β+STA	Surface	Long.	109	27						
					Trans.	105	23						
				Midthk.	Long.	107	26						
					Trans.	105	24						
EPY (WWW)	293708	1	β		Long.	112	23	1561	0.05	0.02	0.009	0.088	0.0036
					Trans.	116	23	1352					
			β+A		Long.	114	24						
					Trans.	117	25						
EPT (SWW)	293708	1	α+β		Long.	121	16	1215	0.05	0.02	0.009	0.088	0.0026
					Trans.	129	15	1070					
			(α+β) + A		Long.	122	16						
					Trans.	129	14						

Note: Tension and Charpy V-notch impact specimens were tested in duplicate.

Structure: W - Widmanstätten such as that produced by cooling from heat treatment above the beta transus temperature; WWW - Weakly worked Widmanstätten; SWW - Strongly worked Widmanstätten.

Rolling Practice: β - rolling from above the beta transus temperature; α+β - rolling from below the beta transus temperature; A - annealed at 1200 °F - 2 hr - AC; ST - solution treated 1875 °F - WQ, 1 hr for 1-inch and 1½ hr for 2.5-inch plate; STA - above solution treatment plus age at 1200 °F - 2 hr - AC.

TABLE 8 Miscellaneous Physical Properties of Ti-100

Modulus of Elasticity in Tension*: 17.0×10^6 psi, (117.2×10^9 newtons/meter^2)

Modulus of Elasticity in Compression*: 18.3×10^6 psi, (126.1×10^9 newtons/meter^2)

Coefficient of Linear Expansion [72° to 1200 °F (20 ° to 650 °C] 5×10^{-6} in./in./°F (9×10^{-6} cm/cm/°C)

Density [86 °F (30 °C)] 0.162 lb/in.^{3} (4.48 g/cm^3)

Magnetic Properties: nonmagnetic

* 1-inch-thick plate.

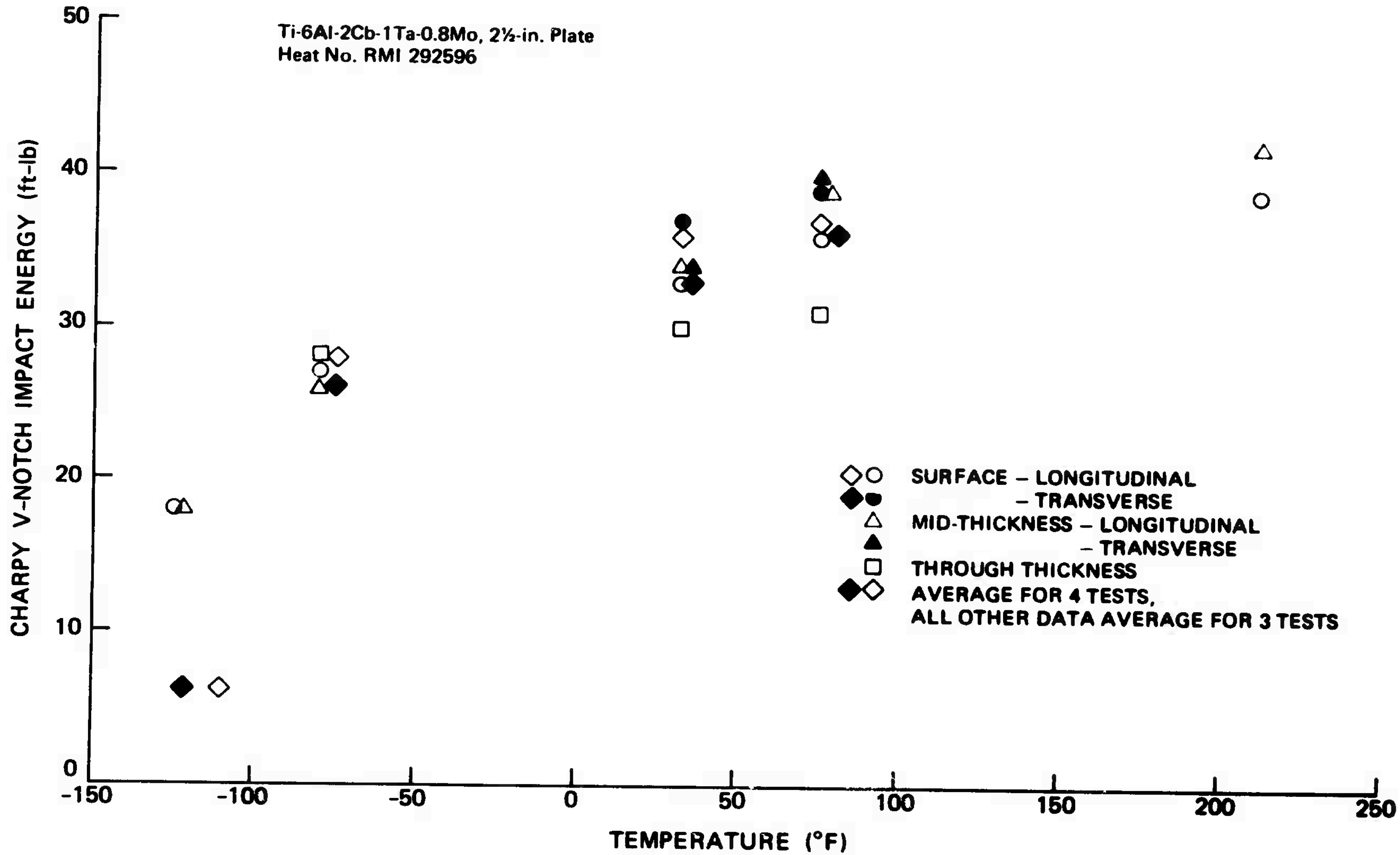


FIGURE 13 Charpy V-notch energy absorption for 2½-inch-thick Ti-6Al-2Cb-1Ta-0.8Mo alloy [21]

TABLE [illegible] Typical Strength and Toughness Data for 1-inch Plate [illegible]

Heat No. & Condition	Orientation	Room-Temperature Yield Strength (ksi)[d]	Room Temperature Test (ft-lb)	Room Temperature Avg. (ft-lb)	[illegible] Test (ft-lb)	[illegible] Avg. (ft-lb)	[illegible] Test (ft-lb)	[illegible] Avg. (ft-lb)
292596 as-rolled[a]	Long.	(not reported)		45		50		41
	Trans.			41		39		40
29255 as-rolled[a]	Long. (area 1)[b]	(not reported)		43		40		30
	Trans. (area 1)			46		[illegible]		35
	Long. (area 2)			40				31
	Trans. (area 2)			40				29
302289 as-rolled	Long.	110.7	39		35		21	
			[illegible]	39	36	35	27	25
	Trans.	113.5	33		[illegible]		20	
			33	33	31	[illegible]	22	21
293708AB as-rolled	Long.	123.4			[illegible]		11	
					19		11	
					20	19	15	11
Ann. 1910 °F-1 hr FC[c]					38		27	
	Long.	105.3			39		28	
					40		29	
					42	[illegible]	34	29
293708B	Long.	108.[illegible]			42		25	
					[illegible]		25	
						35	26	25
293708P Ann. [illegible] °F-1 hr FC	Long.	102.7			[illegible]		33	
					[illegible]		33	
					45		34	
					45	43	34	33

[a] Average of 3 tests each value.

[b] Two areas of the plate sampled in order to assess uniformity of mechanical properties.

[c] FC - furnace cooled.

[d] Average of two tests.

doubled the impact energy values. It may be noted that the yield strength of the as-rolled plate was an unusually high 123 ksi. It was lowered to 105 ksi by the beta anneal. The 1-inch plate of Heat No. 293708B exhibited good impact resistance in the as-rolled condition and was increased by about 30 percent by an anneal approximately 70 °F (21 °C) below the beta transus (i.e., 1790 °F (977 °C)--1 hour--furnace cooled). Yield strength dropped from 108 to 103 ksi.

Figure 4 presented RAD comparing the DT energy spread for plate metal and weld metal. Note that the DT energies for plate metal range from 1500 to 2500 ft-lb depending upon the strength and are well above the $(K_{Ic}/\sigma_{ys})^2 = 1.0$ limit.

4. Machinability of Ti-100

Titanium alloys are somewhat more difficult to machine than steel. In general, surface finishes obtained in machining titanium are better than those of most other materials; however, one exception is in the grinding operation.

Titanium chips have a tendency to gall and weld to the cutting edges of the tools, thereby promoting tool wear failure. This is particularly prevalent after the tool starts to wear so the cutting tool should be replaced before it becomes excessively dull. It is characteristic of titanium to produce a high shear angle between the workpiece and chip during cutting. This results in a thin chip flowing at high velocity over the tool face and this causes high tool tip temperatures to develop. The low thermal conductivity of titanium and the small contact area between the chip and the cutting edge of the tool further contribute to the high tool tip temperature.

The rigidity of the entire system is very important in minimizing galling and welding in machining titanium alloys. Emphasis should be placed on using sharp tools to prevent galling and seizing and therefore, tool failure. Generally relief angles greater than those employed in machining steels should be used since titanium does not work harden to an extent that is detrimental to machining.

Cutting fluids containing chlorides are very effective in the machining and grinding of titanium; however, chlorides cause stress corrosion of titanium components particularly those subjected to elevated temperatures including stress relief anneals. As a result, if choloride fluids are used, carefully controlled cleaning procedures are essential.

Specific recommendations for machining Ti-100 are given in Machining Data for Titanium Alloys[18] under instructions for Ti-7Al-2Cb-1Ta, the predecessor of the Ti-100 alloy.

5. Metallurgical Characteristics of Ti-100

The 6 weight percent aluminum limit and the presence of one or more elements from the group of isomorphous beta stabilizers (consisting of columbium, molybdenum, tantalum, and vanadium) present in the candidate alloy are the result of considerations establishing a minimum level of toughness and resistance to stress corrosion. The stress corrosion mode of these alloys is a natural acuity crack loaded in plane strain and in the presence of sea water. Resistance to stress corrosion may be taken to mean that the threshold value of plane strain fracture toughness in sea water is at least 70 percent of the ASTM standard value in air. Aluminum is the most potent solid solution hardener of titanium on a strength-to-density basis of all substitutionally soluble metals; however, for high toughness and resistance to stress corrosion, the aluminum content cannot exceed 6 weight percent. This limitation is imposed by the occurrence of the intermetallic compound Ti_3Al and by its detrimental effects on toughness properties and upon resistance to stress corrosion.

Crossley has shown that the solid solubility of aluminum in titanium is only 4 weight percent at 930 °F (500 °C). Oxygen acts to decrease solubility of aluminum in titanium, thus increasing the quantity of Ti_3Al and consequently its detrimental effects at a given level of aluminum. For example, 0.1 weight percent oxygen decreased aluminum solubility by 0.6 weight percent and titanium alloys containing 7 and 8 weight percent aluminum suffered degradation of impact toughness when aged to promote the rather sluggish Ti_3Al precipitation reaction.[23] Ternary additions of zirconium, columbium, molybdenum, and vanadium are reported to slow the degradation of toughness in apparent concert with their effects in retarding the kinetics of Ti_3Al precipitation The compound Ti_3Al is brittle; for ordinary aging times the precipitate is coherent. The Ti_3Al is smaller than the matrix, and under ordinary conditions of occurrence is under hydrostatic tension. It, apparently, is a very effective sink for hydrogen.[24]

The phenomenological relationship between increasing aluminum and degradation of resistance to stress corrosion has been well documented. Lane and Cavallaro report that a Ti-3Al alloy had the same fracture stress in seawater as in air. However, when tested in seawater rather than air, marked drops in fracture stress were observed for binary alloys containing 5 to 8 weight percent aluminum and fracture stress decreased progressively with increasing aluminum.[25] Sagle, et al. report for Ti-Al-O alloys that stress corrosion occurred either when oxygen exceeded 0.1 weight percent at 6 weight percent aluminum or when aluminum exceeded 6 weight percent at 0.1 weight percent oxygen.[26]

Since Ti_3Al occurrence is a precipitation phenomenon, its quantity and distribution are influenced by heat treatment and cooling rates as well as by aluminum and oxygen contents. The quantity of compound is minimum or is suppressed entirely when alloys are rapidly cooled from temperatures of 1500 °F (816 °C) or higher. Slow cooling, particularly of heavy sections, may be very detrimental in terms of Ti_3Al precipitation.

Apart from the aluminum-oxygen interaction in promoting the occurrence of Ti_3Al, oxygen degrades impact and fracture toughness as an interstitially soluble solid solution hardener. In order to meet an oxygen specification of 0.08 weight percent maximum, Ti-100 is made with high-purity sponge having a maximum oxygen content of 0.05 weight percent. In comparison, the standard grade of titanium alloys has a 0.2 weight percent maximum oxygen specification and the ELI (extra low interstitials) grade of alloy has an oxygen maximum of 0.12 weight percent. It is apparent that Ti-100 imposes special requirements on the base sponge in terms of purity. In order to maintain this low level of oxygen, care must be taken to remove surface contaminated layers when the material is heated in air and to prevent oxygen pickup during welding.

Hydrogen contamination is another source of toughness degradation in titanium alloys. Hydrogen may be picked up quite readily by heating in a gas-fired furnace operating to produce a reducing environment, by acid pickling improperly, and by insufficiently careful welding. Particular care must be taken to insure that the filler wire has a low hydrogen content, and it could be desirable to have the wire hyrdogen content at least as low as that of the plate (80 ppm, 0.080 weight %).

One additional phenomenon exhibited by Ti-100, which is not observed with HY-180, is room-temperature creep. Significant room-temperature creep is exhibited in Ti-100 at room temperature at stresses below the yield strength. Figure 14 shows creep strain in Ti-100 as a function of time for values of applied stress ranging from 81 to 105 ksi. Note for example that 81 ksi in 500 hours resulted in a strain of 0.1 percent, a stress representing 79 percent of the static yield strength of the material tested. Obviously, the designer of high-strength materials should be conversant with the implications of this idiosyncracy of Ti-100; however, the phenomenon may not be entirely detrimental. The effect of room-temperature creep on the residual stresses in weldments should be beneficial and requires study. If one assumes that 0.2 percent offset yield strength stresses exist, substantial relaxation could be expected within a reasonable time even at room temperature. (Figure 14).

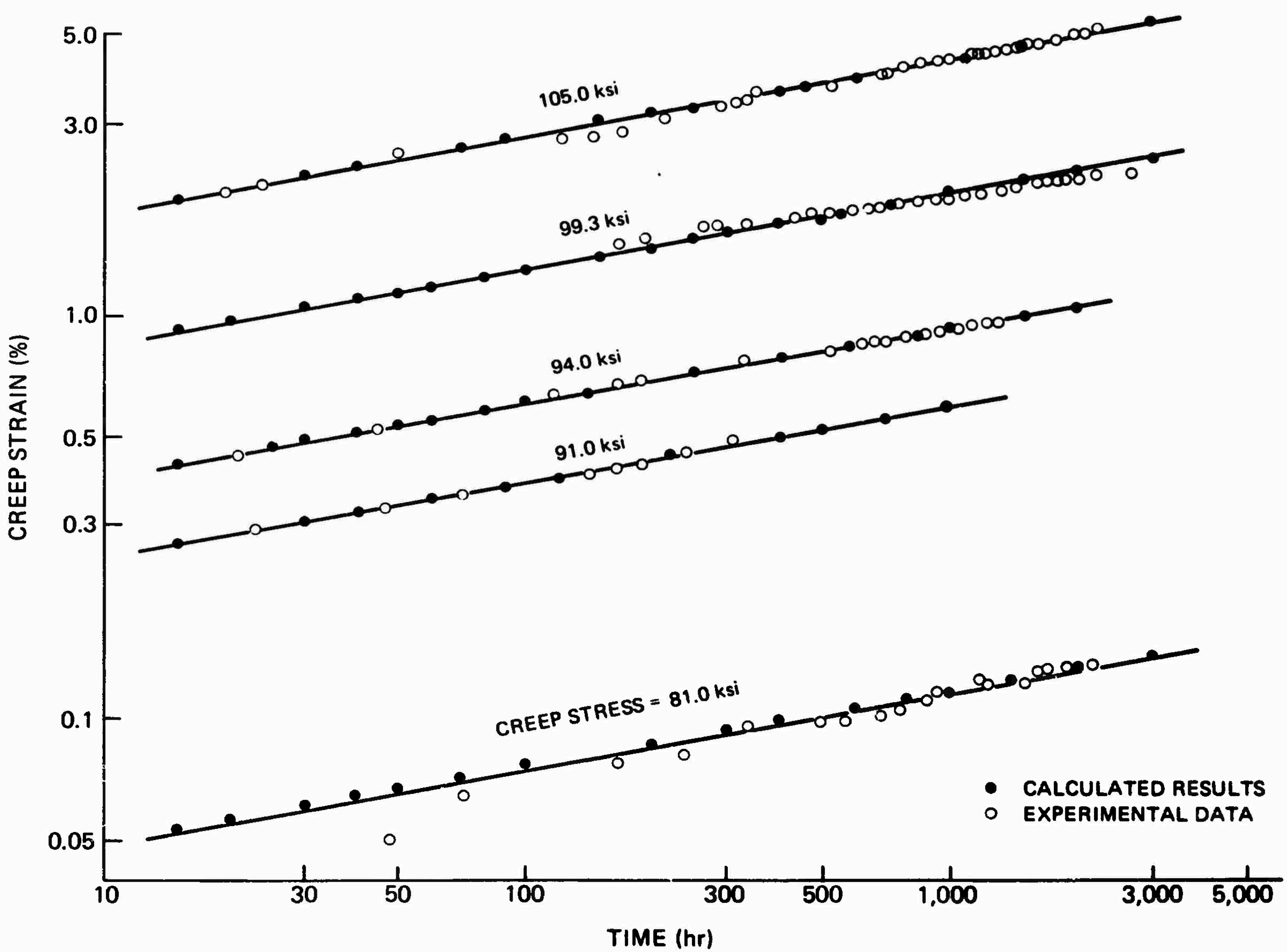


FIGURE 14 Room-temperature creep data on Ti-100 (from reference 27).

IV. PROCESSES FOR WELDING HIGH-STRENGTH STRUCTURES

HY-180 steels and the equivalent classes of titanium alloy are of great interest but present great potential problems. Both of these alloys systems must provide high toughness as well as strength, a combination achieved only with weld metals having a high degree of purity. Nitrogen, oxygen, hydrogen, and carbon levels must be kept relatively low, and weldments in the systems must be free of defects such as slag inclusions, lack-of-fusion or microcracks large enough to act as nuclei from which larger cracks could develop or, if present in sufficient numbers, could reduce the effective section thickness. In other words, the integrity of the welds must be as good as that of the plate.

Two classes of structure must be considered since their requirements differ. One is typified by structures such as airframes and hydrofoils that are made of relatively small and easy to position sections, must be light and designed with small safety factors, and are built in almost ideal environments. These welds must be of high quality and the use of sophisticated equipment and techniques may be required. The other class of structure is typified by pressure vessels that are made of thick sections, and are so massive that positioning and good fit prove virtually impossible. Although such structures are often fabricated with lower strength materials in relatively dirty, cluttered, and drafty facilities by less sophisticated techniques, it is certain that HY-180 will not be fabricable under such conditions.

Because of the importance of multiple heat treatment with HY-180 steel, the alterations or properties developed in heat-affected zones must be given careful consideration. Weld repairs may produce micro or macro defects that may be significant in controlling the mechanical properties or in producing critical size flaws. It is certain that weld defects will be detected in some zones of a structure and that a weld repair procedure must be qualified. Past experience indicated that repair of such welds may develop new flaws much more severe than those the repair was to correct.

Welding is one of the major items of cost in fabricating the lower strength alloys now being used, and higher cost anticipated due to the greater care and control required by the high strength materials may preclude their use. In the shipyards, older processes such as covered electrode welding must be replaced with more reliable but more complex processes that are less flexible and more massive. As a result, complex structures may have to be redesigned to accommodate these welding processes. In addition, the welding devices must be reduced in size since it will be impossible to design and build functional, economical structures with clear access to every joint to be welded using present means.

The properties of weldments made with the iron-nickel-cobalt alloys typical of HY-180 plate composition are sensitive to energy input and wire cleanliness. For a given alloy and process, the weld metal strength and toughness are inversely dependent on energy input. Weldments made with the hot wire gas tungsten arc (GTA) process characteristically lose 20 ksi and 20 ft-lb of shelf energy for each increase of 10 kJ/in energy input.[28] When using the GMA helium process, a decrease of 10 ksi and 10 ft-lb in shelf energy is noted for each increase of 10 kJ/in. The gas metal arc (GMA) helium process produces weldments that have a lower shelf energy than the hot-wire GTA process. This effect has been ascribed to a difference in the cleanliness of the weldments, the hot-wire GTA process seems to bake contaminants off the wire before it enters the welding zone while the GMA helium process does not.[29] This rather striking effect is significant since GTA weldments show high elastic-plastic DT results while GMA weldments do not.

The influence of energy input and wire cleanliness on mechanical properties indicates that processes and filler material improvements are needed. Interestingly, the hot-wire plasma-arc process produced a weldment with fully plastic DT behavior at 180 ksi yield strength even though the weldment was made at 125 kJ/in.[29, 30] This result suggests that process research may be more fruitful than filler wire research in improving weldment performance although the latter still requires extensive investigation. Wires that are developed should be tolerant of the reasonably high energy levels required by some of the more functional processes if they are to produce satisfactory welds at relatively low cost. Currently available are filler wires that can provide deposits meeting both strength and ductility requirements if oxygen, nitrogen, and hydrogen contamination can be controlled. However, except for the low-deposition-rate processes, limitations of presently available processes prevent meeting these contamination limits. Although welding processes constitute the major unsolved problem in the joining of high-strength materials, improved filler metal compositions are needed to provide more latitude for process variations.

When possible, the primary joints should be fabricated with devices that incorporate adaptive controls to compensate for irregularities in fit-up and edge preparation. Nonetheless, a sizeable percentage of the welds must be made manually.

The welding processes that should be used for fabricating airframes and ships can be classified in four categories: those that use slag, those that are totally mechanized and require precise fit-up of the joint, those that use tungsten electrodes as the primary source of heat with solid wire as filler metal from a second source, and those that use wire both as the source of heat and filler metal. The following discussion will focus on these categories.

A. Slag Processes

Slag processes include those using covered electrodes, fluxcored electrodes, and solid wires submerged in a powdered flux.

1. Shielded Metal Arc (Covered Electrode)

Covered electrodes are the simplest of all devices for welding but require a considerable amount of weldor* skill. While mechanization is not practical, covered electrodes can be used to make welds in all positions and in all plate thicknesses. This process uses the smallest and lightest mechanical devices, allowing welds to be made in very tight quarters. Unfortunately, the slags and reactive gases involved react with titanium and are a source of embrittling inclusions in high-strength steels. Some moisture must be present to insure

* The term "weldor" refers to the operator; "welder" is an item of equipment.

adherent coatings; therefore, unless rigorous baking is used hydrogen can be a real problem when welding high-strength steels. With covered electrodes, the chances of achieving the 90 ft-lb shelf energy considered necessary for HY-180 steel are remote, and even the odds of producing a 50 ft-lb shelf energy are not encouraging. Covered electrodes are not efficient to use and the cost of producing weld metal with this process is significantly greater than that possible with the gas-shielded wire processes. It is believed that this process has little potential for welding high-strength steels and none for welding titanium alloys.

Flux-cored wires of interest use carbon dioxide or argon-carbon dioxide mixtures for shielding the arc. This process is much easier to use than the covered electrodes and is far more efficient and less costly. All-position capability is excellent and the slags help to minimize defects. However, cored-wire technology is not sufficiently advanced to produce welds as tough as those made with covered electrodes, and, as presently constituted with oxides and other non-metallics in the core, it should not be expected to produce the properties needed for joining high-strength steels for some time or to be useful for joining titanium at any time. Future generations of wire cores may be formulated unconventionally with active or volatile metallic powders that ordinarily cannot be retained in solid wire alloys. Calcium, for example, may be introduced in relatively rich concentrations as a powdered alloy of calcium and silicon, and when protected with a shield of argon or argon-helium rich gas, this type of cored wire could offer significant advantages.

2. Submerged Arc Welding

Submerged arc welding can be used only in the flat position and, because energy input must be kept relatively low when welding high-strength materials, its primary advantage of producing massive welds cannot be exploited. Also, because of the limitations of currently available fluxes that create problems similar to those mentioned above, there is little potential for the submerged arc process, unless new oxygen-free flux systems and improved techniques are developed.

B. Specialized Processes

Specialized processes require extremely precise fit-up and positioning of the joint to be welded. In addition, process parameters such as the travel speed, current, and voltage must be regulated within close tolerance and the source of heat must track the joint precisely. Generally speaking, the equipment associated with these processes is massive and expensive and a considerable learning period is required if it is to be used effectively. However, the advantages include low energy input, minimal distortion, and a capability for unusually high-quality weldments.

1. Electron Beam Welding

The electron beam is the most commonly used of the specialized processes. This equipment uses accelerating voltages in excess of 30,000 necessitating careful insulation of the conductors and careful shielding against the x-rays produced. Deep penetration welds can be made only in a vacuum, requiring either chambers and positioners of adequate size to accommodate the component being welded or difficult-to-maintain sliding seals around small evacuated chambers that move along the joint. The welds are narrow and deep but can be completely sound if the joints are carefully mated and free of contaminants and if the beam is directed precisely on the joint; however, these criteria are not easy to satisfy. The stray magnetic fields common in high-strength steels can cause a real problem in deflecting the beam, but no such fields are encountered in titanium alloys. The process has been used very effectively by airframe manufacturers and will continue to be used by that industry because of its unique capabilities, but there are reservations about its use in shipyards since ships cannot be built in evacuated chambers. Acceptable sliding seals are not likely to be developed, and moving such massive equipment around a complex structure appears to present insurmountable problems. Furthermore, the joints probably cannot be prepared economically with the precision needed, and they must be kept free of debris. High voltage and x-rays need to be guarded against.

2. Laser Welding

Lasers having sufficient power to weld 3/4-inch-thick plate have been developed and the rate of growth of this technology has been so phenomenal that within a few years devices may be available to penetrate 2-inch plate; if so, the weld fusion pattern is expected to be similar to that produced with an electron beam, meaning that the same precise machining, mating, and cleaning of joints will be required. However, evacuated chambers will not be needed, and x-rays will not present a hazard. While inert shields will have to be provided, containment chambers can be made of transparent materials and present no real problem. If a totally coherent laser beam can be produced, it might be directed to the joint with optical devices, requiring only the movement of relatively small light-focusing mirrors rather than the entire emitting source. Sufficiently powerful and coherent lasers probably will cost in excess of one million dollars. The major technical obstacles to their use appears to be the need for precise machining and fitting of the mating components of the structure and the need for extensive safety precautions.

3. Narrow-Gap Welding

Narrow-gap welding is a highly specialized adaptation of the GMA process that directs small-diameter wires and a shielding gas into a deep, narrow cavity having precisely spaced and parallel walls. It has potential for saving time for welding and reducing distortion. The energy input to the weld is low, which is a real advantage for joining high-strength materials. Precise fit-up is essential for achieving uniform, defect-free welds because the alignment and spacing of the parts are critical. Also, the process may have some of the restrictions of conventional GMA welding discussed below. Narrow-gap welding also has been plagued with contact-tube problems and, because of the low energy input, with lack-of-fusion defects. Back-up materials are still causing some difficulty and unobstructed access must be provided to the joint. The chance of rotating the rather massive apparatus around a full circumferential joint is remote. Also, the welds will be difficult to make in quadrants unless some method is developed for achieving good and uniform reinforcement where the individual welds had been interrupted. The problems outlined are not unresolvable but the overall cost-effectiveness of the process as a shipyard tool remains questionable primarily because of the fit-up and guidance problems.

C. Electro-Gas and Electro-Slag Welding

The electro-gas and electro-slag processes, although used more commonly in conventional shipbuilding, have not been considered in this discussion because of their extraordinarily high energy input, which would cause excessive degradation of the mechanical properties of the weldment.

D. Tungsten Arc Processes

Tungsten arc processes rely on the arc energy developed between a non-consumable tungsten electrode and the work piece. Alternating current is commonly used with argon shields when welding aluminum or titanium to obtain the cathode sputtering that removes oxides from the vicinity of the weld crater; when penetration is required, direct current is used and helium is the better shield gas. In virtually every application where high deposition rates are necessary, direct current is used with the tungsten at the negative pole. Since the work piece is the anode, the desirable cleaning action cannot be used to advantage. Argon, helium, or mixtures of the two are almost always used to shield the arc although hydrogen may be added when the arc is constricted as in the "plasma arc" process.

1. Conventional Gas Tungsten Arc Welding

Conventional GTA welding often is used, in spite of its cost, when weld integrity is essential. Costs are high as a result of the low deposition rates when filler metal is provided by feeding cold wire into the arc. The wire must be clean to prevent contaminating the weld pool. When used manually, the process requires great dexterity on the part of the weldor since he must control the arc with one hand and the filler wire with the other. The process can be mechanized by attaching a guide to the welding torch through which wire is fed at controlled rates from a spool. It has been used with great success to weld a wide variety of metals in all thicknesses. However, its use has been limited to critical mechanized high-quality applications because it requires considerable manipulative skill.

2. Pulsed GTA Welding

The pulsed GTA process was developed to achieve better control of the weld pool in all positions of welding by allowing the pool to freeze periodically. With this technique, current is pulsed from a background level sufficiently high to sustain the arc (yet too low to sustain the size of the molten pool) to peaks sufficiently high to provide the energy needed for welding. The pulse period ranges from 0.1 to 2 seconds per pulse. Manual welding is made easier because the weldor can use the pulses to time his progression and the weld pool is easier to control. Mechanized welds also are easier to make in all positions. Because the pool is less sensitive to its orientation, a single power supply setting can be used for depositing metal around the full circumference of a pipe or other symmetrical structure. Thus, better quality is achievable without sophisticated programming devices. Even though used extensively now for automatic pipe welding, the pulsed GTA process is not in more general use because the deposition rates are not increased beyond those of the conventional GTA process.

3. Hot Wire GTA Welding

The hot-wire GTA process was developed as a method of increasing the deposition rate of the GTA process while still maintaining the basic advantages of this process over the GMA process. This is accomplished by supplying substantially all of the energy to melt the filler wire by resistively heating the wire itself before it enters the weld pool. The arc for melting the base plate is unchanged from the conventional GTA process. The heated wire enters the weld pool at its melting temperature and, since it is not transferred across an arc, alloy additions are not lost by evaporation or oxidation. The arc shielding gas is normally a mixture of 75 percent helium and 25 percent argon. In a typical weld, the energy involved in resistively heating the filler wire is about 25 percent of the arc energy.

Since this process does not require the use of oxidizing gases to facilitate metal transfer, weldments with a very low oxygen content can be made in steel. It has been shown that with the use of trailing shields, oxygen contents of less than 10 ppm can be easily obtained in steel weldments, even though the oxygen level of the wire is often substantially higher. It is believed that this effect is due to flotation of inclusions during welding. The porosity level of hot wire welds is lower than that of cold wire welds made with the same wire probably because of the decomposition and evaporation of surface contaminants (such as drawing lubricants) in the wire during resistive heating.

The GTA hot wire process has been used successfully to weld a number of high-strength materials including both steel and titanium alloys. Typical results are shown in the following section.

If the ratio of travel speed to deposition rate (and therefore bead size) is maintained constant, the appearance of weldment structures will be similar for both the conventional GTA and the GTA hot wire processes. However, at high deposition rates it becomes impossible to realize corresponding increases in travel speed because of undercut and lack of fusion. Therefore, the bead size of high deposition rate (15 lb/hr) hot wire welds will be larger than the bead size of typical cold wire welds and the detrimental influence of less weldment refinement will become apparent in reduced toughness. The overall deposition rate appears to be limited by magnetic interaction between the preheat and arc currents that causes the arc to become distorted. Although an improvement over the conventional GTA process, the hot wire process has not been used for manual welding and may be restricted to the flat and horizontal positions.

4. Plasma Arc Welding

The plasma arc process is a modification of the GTA process using an orifice to concentrate the plasma, thus intensifying the arc energy at the plate. With proper control, the plasma arc can be made to produce a small keyhole in the weld crater, which allows deeper penetration and significantly higher travel speeds to be obtained. It can be used to weld all alloys thinner than 3/8 inch and is particularly useful for making long welds such as those encountered in tube mills. Hydrogen additions seem to help form a better weld but in those cases where it must be used, the alloy should not be sensitive to the presence of this gas. The process lends itself to a number of aerospace applications that can be mechanized, but it is expected to have little potential for applications in shipyards except in fabrication of high-performance ships and possibly pipe welding.

E. Gas Metal Arc Welding

There are many variations of the GMA process; however, only those versions capable of being used with oxygen-free shield gases are pertinent to this discussion about welding high-strength alloys. To date, the GMA process has been used with direct current reverse polarity making the plate the cathode. As a result, thermionic materials either in the plate, wire, or shield gas can have a significant effect on the uniformity of the weld, its shape, and defects such as undercut. The wire surface condition also is important and contaminants such as drawing lubricants can introduce excessive levels of hydrogen into the weld pool. Effective shielding is important, and at relatively high current levels, the radiation from the transparent argon shielded arc can be sufficient to require water cooling of the gun nozzle. To ensure good shielding and trouble-free operation under such conditions and to allow unimpeded feeding of both the gas and wire to the arc, the torch has to be relatively cumbersome, relatively heavy, and somewhat awkward to use in confining quarters. Sporadic attempts have been made to simplify the equipment, to reduce its size, and to consolidate it into a self-contained package; however, the resulting devices have received mixed reactions, and no sustained effort has been made to produce such specialized equipment because the need was not sufficient to justify the expenditure.

1. Conventional GMA Welding

Conventional GMA welding of non-ferrous metals, including titanium, is done routinely using shields of argon or argon-helium mixtures. In these gases, the spatter-free spray transfer and cathode cleaning unique to GMA welding are used to great advantage, particularly in the flat position. The relatively high duty cycles and high deposition efficiencies make the process cost effective and it can be either mechanized or used manually. Constant potential power supplies produce an essentially self-regulated arc length, making the process easy to control. Major problems include aspiration of air into the system and porosity resulting from contamination of the weld pool by dirty wire and/or joints.

When welding steels, problems can develop because traces of oxygen in or on the plate cause the arc to seek out those sites having the lowest work function and, thus, to wander erratically. These effects are counteracted by doping the argon shield with small amounts of oxygen, thus producing a uniform oxide layer on the weld and forcing the arc to be anchored at the weld crater. As a result, the weld contour is improved significantly. In the commonly welded steels, these oxygen additions have no real effect on mechanical properties and even can improve them by minimizing undercut and subsurface mechanical discontinuities. Filler metals with a tolerance for oxygen have been developed to join the HY-130 steels and the GMA process is being used successfully for fabricating those materials in the flat and horizontal positions. However, the toughness of HY-180 weld metal is so impaired by oxygen that the argon-oxygen mixtures conventionally used for GMA welding cannot be tolerated.

2. <u>Short Circuiting GMA Welding</u>

Short-circuiting GMA welding was developed for joining sheet steel using either carbon dioxide or argon mixed with 25 percent carbon dioxide to shield the arc. This technique relies on direct short circuits between the electrode and the weld pool to transfer molten drops from the wire tip. Special constant potential power supplies with controlled inductance are used to control the dynamic response of the arc to the current surges, and wires having diameters less than 0.045 inch must be used. When the wire feed and power supply settings are properly proportioned, the short circuits occur at rates between 50 and 150 per second, and relatively little spatter is generated. Little skill is needed to make sound welds in sheet steel in all positions. Unfortunately, plate thicker than $\frac{1}{4}$ inch extracts heat from the weld pool so rapidly that unfused regions can be produced when unskilled weldors use the process. The problem is complicated by the need for a more inert shielding gas for joining high-strength steels. Mixtures of argon and helium containing small amounts of carbon dioxide have been developed for this purpose but even with such shielding gases skilled weldors are needed for all-position welding where high quality is mandatory.

Carbon dioxide cannot be used in shield gases when joining titanium alloys. Good results have been reported with helium-rich mixtures of argon and helium; however, the arc polarity had to be changed to direct current straight polarity to obtain the best combination of penetration and arc stability. Based on the frequency of defects found in steel weldments, some authorities have questioned the general effectiveness of this process for joining titanium in heavy sections in pressure vessels.

3. Pulsed GMA Welding

Pulsed GMA welding is a relatively recent modification of the argon shielded process and requires a special power supply that pulses the current at regular periods from a background level sufficient to sustain the arc to a level just above that needed to produce spray transfer. The frequencies commonly used are 60 and 120 Hz. This pulsing action significantly reduces the average current and decreases deposition rates while maintaining spatter-free deposition. Consequently, the weld pool can be small enough to be supported in all positions. This type of arc projects molten droplets axially from the tip of the wire without significant gravitational influence, an additional advantage in out-of-position welding. The process is being employed manually to make welds in all positions using shields of argon mixtures containing small amounts of oxygen similar to those mentioned previously. As for other all-position processes, considerable operator skill is required; however, experience in 130 ksi steels for a given level of operator skill resulted in welds containing few defects. The process also has been mechanized with considerable success to make welds in all positions. Like the conventional GMA-spray process, its primary deficiency for joining HY-180 classes of steel is the need for oxygen to stabilize the arc. Also, if the shielding is not carefully controlled, the possibility of air being aspirated into the arc is increased.

This process has been used with reasonable success for making welds in the overhead and flat positions. However, experience has been so limited that the pulsed-GMA process cannot be considered a proven tool for welding titanium alloys, and concern has been expressed about controlling the effectiveness of the shielding gas stream.

4. GMA-Helium Welding

GMA-helium welding is a departure from the traditional argon-shielded process designed to prevent the surface irregularities of welds made in oxygen-free gases. The cathode sputtering found with argon does not occur with helium. However, the totally inert shield permits very tough welds to be produced in HY-180 steel.[36] Helium has not been used previously in GMA welding because the metal transfer tends to be globular and spattery. The name GMA-helium process (GMA-He), is used to describe the GMA process as modified to operate in a totally inert shielding atmosphere of helium. GMA-He welding is done using a reverse-polarity metal arc. Wire is introduced into the arc at a constant rate at a 30 degree angle from the vertical with the tip leading. The mode of metal transfer is normally short circuiting, although free-fall globular transfer is obtainable at higher voltages. Spray transfer has never been observed. Short circuiting transfer, the preferred mode of operation for out-of-position work, is normally obtained with voltages in the range of 23 to 30 volts. Higher voltages result in globular transfer. The required voltages for short circuitive globular transfer depend on the wire size, wire feed rate, and wire stickout. As the voltage is raised, the frequency of shorting decreases. Typical shorting frequencies are 20 to 50 shorts per second and provide a stable range of operation. Higher than normal slope and inductance have been found to be necessary in order to obtain minimum spatter.

The process is still in the developmental stage and not yet commercially available. However, it does appear to offer an all-position capability, either manual or mechanized, to deposit oxygen-free weld metal at respectable deposition rates (5 to 15 lb/hr) and merits further development.

5. Emissively Coated Wire GMA Welding

Emissively-coated wire GMA welding is a modification of the argon shielded process and uses a wire treated with substances that promote stable spray transfer with either direct current straight polarity (D. C. S. P.) or alternating current (AC) in pure argon. Ordinarily, the metal transfer in argon with either straight polarity or alternating current is globular and unstable; however, when the wire is treated to reduce its work function, the transfer can be stabilized and the plasma conductivity is improved. When properly treated to control heat balance and shielded in pure argon, such wires have been used to produce spatter-free welds both in the flat position with conventional constant potential power supplies and in the vertical position with pulsed-current power supplies. Both manual and mechanized techniques have been used with conventional equipment and procedures.

The presence of oxygen in weldments is known to have a negative effect on the shelf level of toughness. Data are available showing that increases in HY-180 weld metal oxygen from 20 ppm to 400 ppm can reduce Charpy V-Notch toughness from 80 ft-lb to 10 ft-lb.[28] Other data suggest that the effect may be more severe than this.[31] Part of the explanation for the variation in response to oxygen has been shown to be related to the distribution of oxygen as oxides in the weld metal.[32] The use of treated wires with direct-current straight-polarity eliminates the need for oxygen additions to the shielding gas to stabilize the arc. Thus, a significant source of oxygen is removed from the arc and the probability of achieving excellent toughness is improved.

For some reason less nitrogen and oxygen are transferred to the weld metal with either alternating current or direct current straight polarity when compared with direct current reverse polarity welds made in pure argon. Typical results are shown in Table 10. Obviously, better toughness should be expected with both the DCSP and AC welds since they are less contaminated with either oxygen or nitrogen. These results have been confirmed with other alloy systems. The ability to use alternating current with treated wires also provides a means of minimizing arc blow.

Treated GMA wires are not commercially available but a feasibility study is currently underway.[33] Obviously, work is needed to demonstrate the relative advantages and disadvantages of hot wire GTA, GMA-helium, and treated wire GMA for depositing tough strong weld metal.

6. Summary of the State of the Art

State of the art: A number of processes can be used to fabricate structures such as airframes and new shallow draft ships. The choice of process depends largely on the quality required, the sensitivity of the alloy to thermal effects in the heat-affected zone, and the investment which can be justified. High-strength steels and titanium alloys are welded almost routinely by the aircraft industry. However, the situation for the massive structures built in shipyards is different.

Heavy sections of titanium have been welded in the flat and horizontal positions using the conventional GMA process and argon shielding, but the conditions were almost ideal. Early work has demonstrated the possibility of using short-circuit transfer to make all-position welds in titanium alloys, but the pulsed-GMA technique has been shown to be more successful. Maintaining shielding is the primary problem when welding titanium, particularly for manual welding since the arc cannot be blocked from view and trailing shields are awkward to handle. Another problem with titanium is related to instability of the arc due to the development of strong unsymmetrical cathode jets that are emitted from the weld crater.

Steels developing yield strengths up to 140,000 psi are reasonably tolerant of oxygen and hydrogen as compared with titanium. They can be welded with many

TABLE 10 Interstitial Content of HY-180 Weld Metal[33]

	C	N_2	O_2
Wire	699	21	117
Weld Metal DCRP Spray Arc Flat Position	525	126	265
Weld Metal DCSP Pulse Arc Vertical-up	601	38	37
Weld Metal AC Spray Arc Flat Position	667	38	45

Note: All analyses in ppm by weight.

processes including SMA and GMA in a variety of forms. Pulsed-GMA has been incorporated into a reliable mechanized process that has been used successfully to weld conventional joints with conventional fit-up. Stronger ferrous metals have a lower tolerance for oxygen and hydrogen. They have not been welded in all positions with commercially proven processes.

It is probable that acceptably strong filler alloys can be developed that will be tolerant of higher energy input than are those available now. The problem is to keep these alloys sufficiently pure to ensure adequate levels of toughness. A variety of mechanized techniques could be developed to achieve these objectives. Those having the greatest odds of success are the hot-wire GTA, treated-wire GMA and pulsed-GMA, and GMA-helium. The alternating current feature of the treated-wire GMA process may prove to be essential because of the strong residual magnetic fields to be expected in these steels. The narrow gap technique may not succeed because of the need for an oxidizing gas and need for careful joint fit-up. The odds of developing a cost-effective electron-beam or laser process appear to be remote. Plasma-arc does not appear to have the capability of penetrating the heavy plates needed in ship construction, although the plasma-arc process is not restricted to the keyhole mode. The use of auxiliary hot wire with the plasma-arc process has produced interesting results in HY-180 plate.[29, 30]

The chances for successful manual arc welding are small. The odds of producing an acceptable covered electrode are remote. Since the conventional GTA process is much too inefficient for joining heavy plate, only the GMA processes that can be used with completely inert gas and hot-wire GTA seem to offer any real potential for joining the classes of steels and titanium alloys under consideration.

V. PROPERTIES OF WELDMENTS

A. HY-180 WELDMENTS

Table 11 summarizes the chemical analyses of some experimental heats of HY-180 used in producing welding wires. Table 12 summarizes welding procedures, mechanical properties, and as-deposited weld metal compositions for some typical hot-wire GTA and GMA-helium HY-180 weldments. From these data it appears that the criteria of 180 ksi yield strength and 90 ft-lb Charpy V-notch energy at 0 °F (-18 °C) are more readily achieved with the hot-wire GTA than with the GMA-helium process. Table 13 summarizes the tensile and impact properties of a series of GTA welds made at low deposition rates (1.0 to 1.3 lbs/hr) together with the chemical composition of the three heats of wire used.

Only limited dynamic tear test data are available for HY-180 weld metal. Although these data indicate that weld metal behavior comparable to HY-180 base metal may be possible, considerably more testing is necessary to evaluate the effects of welding processes and welding procedures.

Figure 15 presents what information is available on the effect of welding procedures on the toughness and other mechanical properties of various regions of the weld heat-affected zone (HAZ). The compressive yield strength and 0 °F (-18 °C) Charpy V-notch energy are plotted as a function of the peak temperature experienced by specimens treated in the Gleeble to simulate various regions of the weld heat-affected zone. It is interesting to note that while the use of a 300 °F (149 °C) preheat significantly increased the as-welded hardness throughout the HAZ, the effect on the impact properties was negligible. Further, it is surprising to note that the coarsened region exposed to a peak temperature of 2400 °F (1316 °C) exhibited the highest toughness. This is in direct contrast to the behavior of ordinary quenched and tempered steels such as HY-80.

The region of the HAZ exposed to peak temperatures in the range from 1300 to 1600 °F (704 to 871 °C) exhibits the highest yield strength and the lowest impact strength. The impact strength is increased significantly by post-weld aging regardless of whether or not preheating was employed.

TABLE 11 Chemical Composition of Experimental HY-180 Welding Wires [34]

LINDE Number	C	Mn	P	S	Si	Ni	Cr	Mo	Co	Al	N	O
10	0.050	0.10	0.003	0.003	0.10	10.3	1.94	1.02	11.7	0.003	0.001	0.0047
11	0.046	0.09	0.004	0.002	0.09	10.5	1.93	1.02	11.8	0.005	0.001	0.0023
12	0.075	0.10	0.003	0.002	0.10	10.2	1.98	1.02	11.6	0.006	0.001	0.0019
13	0.13	0.10	0.003	0.002	0.08	10.5	1.93	1.01	11.9	0.004	0.001	0.0018
14	0.094	0.10	0.003	0.003	0.09	10.4	2.00	1.02	11.7	0.013	0.001	0.0053
15	0.094	0.10	0.003	0.004	0.09	10.4	1.88	1.01	11.9	0.041	0.001	0.0034
16	0.067	0.10	0.003	0.002	0.09	10.0	1.86	0.96	11.5	0.004	0.002	0.0035
17	0.072	0.095	0.044	0.001	0.09	9.6	1.92	0.96	7.8	0.005	0.003	0.0078
18	0.072	0.090	0.004	0.003	0.09	9.9	1.88	0.96	9.8	0.004	0.002	0.0068
19	0.074	0.095	0.003	0.007	0.09	10.1	1.93	1.00	11.7	0.005	0.002	0.0037
20	0.076	0.090	0.003	0.009	0.09	10.2	1.93	0.97	11.7	0.014	0.003	0.0057
21	0.075	0.095	0.003	0.010	0.10	10.5	1.93	1.02	11.9	0.031	0.001	0.0035
22	0.076	0.10	0.003	0.021	0.09	10.5	1.94	1.01	11.8	0.004	0.001	0.0038
23	0.075	0.10	0.004	0.020	0.10	10.5	1.99	1.02	11.8	0.033	0.002	0.0023
24	0.12	0.09	0.004	0.003	0.08	10.0	1.80	0.96	8.5	0.005	0.001	0.0031
25	0.17	0.10	0.003	0.003	0.10	9.7	1.95	0.98	8.4	0.005	0.002	0.0028
26[a]	0.056	0.10	0.003	0.002	0.10	10.4	1.96	1.02	11.8	0.005	0.001	

[a] 0.003 percent cerium added

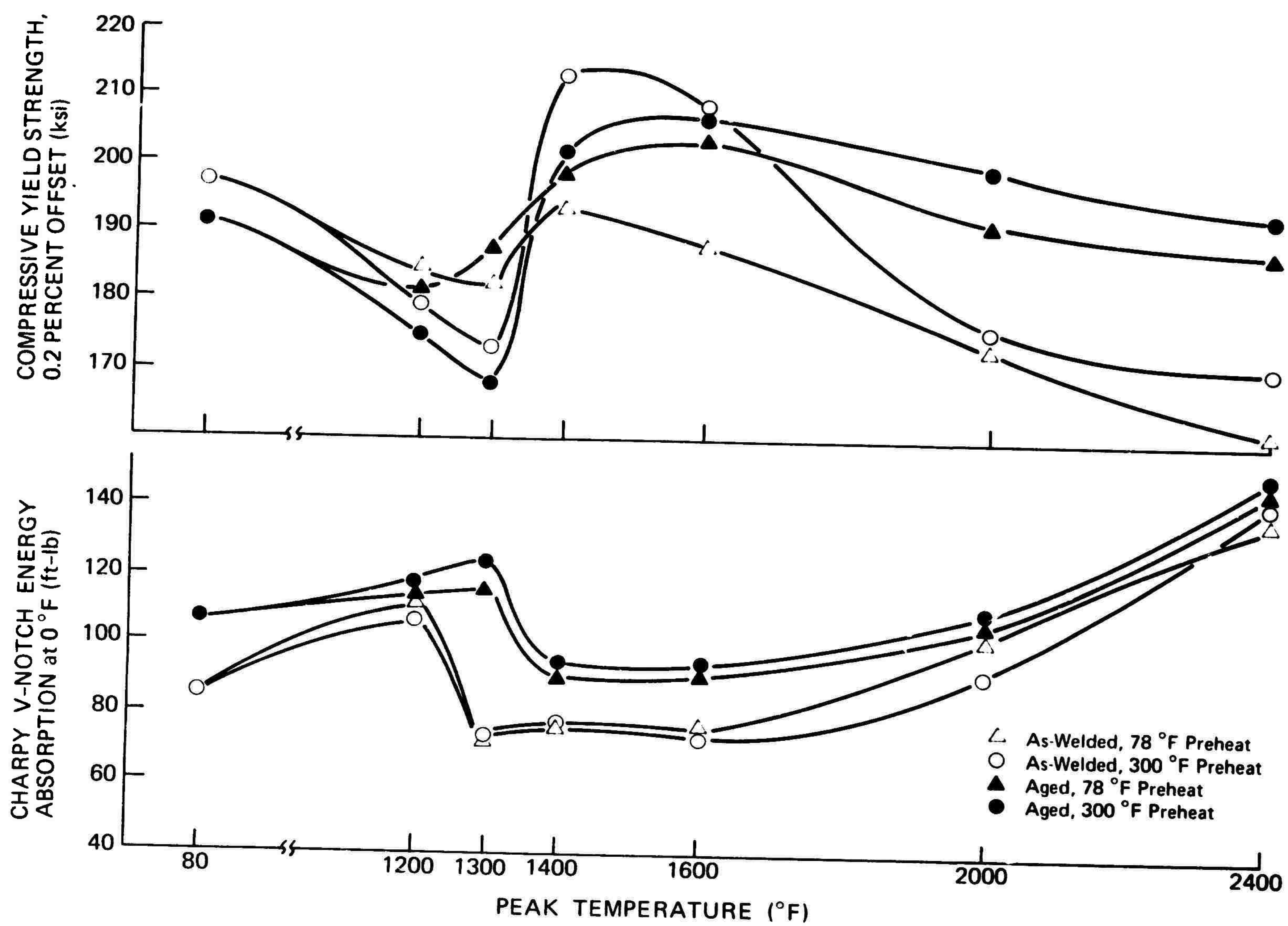


FIGURE 15 Compressive yield strength and Charpy V-notch energy absorption of simulated weld-heat-affected-zone microstructures in HY-180 steel.[11]

The reasons for the anomolous behavior in the yield strength is not clear and warrants further investigation. In fact, the effects of welding procedures on the HAZ should be thoroughly investigated in order to optimize the choice of welding procedures.

B. Ti-100 WELDMENTS

Figure 4 (p. 8) compares the DT energy of Ti-100 weld metal with the plate material and indicates them to be comparable in this respect.

Table 14 presents yield strength and impact strength data for Ti-100 weldments together with a single comparison of the base metal-weld metal DT energies. It is surprising that the Charpy V-notch energy of the weld exceeds that of the plate while the reverse is true of the DT energy (top two rows of data). On the basis of these data and that shown in Figure 4 it would appear that all three welding processes are capable of making weldments that would provide fracture safe behavior in Ti-100 with the properties of base metal, weld metal, and HAZ being roughly equivalent.

Table 15 presents additional data in both as-welded and post-weld heat-treated conditions for both weld metal and the HAZ. Again, these data indicate that yield strengths in excess of 100 ksi with adequate toughness can be achieved in Ti-100 weldments by both GMA and GTA welding.

Table 16 compares the fracture toughness behavior in air and seawater for base metal with that in seawater for manual GTA and semi-automatic GMA short-arc (the latter in both as-welded and stress-relieved). Although the weld made with manual GTA shows only slight degradation the short-arc GMA welds show a significant decrease in fracture toughness. This behavior should be explored further.

TABLE 14 Charpy V-Notch Impact Properties of Ti-100 Weldments[17]

Welding Process	Plate Thickness (in.)	Material	Yield Strength (ksi)	Charpy V-Notch Impact 75°F (ft-lb)	32°F (ft-lb)	-80°F (ft-lb)	DT 32°F (ft-lb)
RMI data	1	Base	107	33			2500
		Weld	113	40			2100
GTA[a]	1	Base			40	30	
		HAZ			43		
		Weld	105				
GMA Spray[a]	1	Base			40	30	
		HAZ			41		
		Weld	108		39		
GMA Spray[a]	1	Base			--	--	
		HAZ			--	--	
		Weld	113[c]		40		
GMA Spray[a]	1	Weld	122[a]			26	
GMA Spray[a]	1	Weld	111[c]				
GMA Spray[a]	1	Weld	108			35	
GMA Short Circuit[b]	2.5	Weld	122[c]			26	
GMA Short Circuit[b]	2.5	Weld	106			26	
GMA Short Circuit[a]	2.5	Weld	111[c]			37	
GMA Spray[a]	2.5	Weld	104			37	

[a] Ti-6Al-2Cb-1Ta-0.5Mo filler metal.
[b] Ti-6Al-2Cb-1Ta-0.8Mo filler metal.
[c] All weld metal specimen

The last 7 lines of data represent two 30-inch diameter, 5000-pound production size heats, No. 292555 rolled to 1-inch plate and No. 292596 rolled to 2½- and 1-in. plates

TABLE 15. Mechanical Properties of Ti-100 Thick-Plate Butt Welds[56]

Welding Process	Material Type (1-in. plate)	Filler Metal: Nominal Composition	Filler Metal: Wire Diameter (in.)	Condition of Weldment	Tensile Properties: Tensile Strength (ksi)	Tensile Properties: Yield Strength 0.2 Offset (ksi)	Tensile Properties: Elongation (%)	Tensile Properties: RA (%)	Location of Fracture	Charpy V-Notch Impact (ft-lb)[a], Test Temperature of 32 F: Weld Zone	Charpy V-Notch Impact (ft-lb)[a], Test Temperature of 32 F: HAZ
GTA	Pilot Heat	Ti-621 0.8	1 x Flat Strip	As-Welded	127	115	9	26	Base Metal	-	19
	Pilot Heat	Ti-621 0.8	1 x Flat Strip	900 F, 2 hr, AC	129	115	10	25	Base Metal	32	11
	Production Heat	Ti-621 0.5	0.062	As-Welded	123	105	11	33	Base Metal	-	43
	Production Heat	Ti-621 0.5	0.062	900 F, 2 hr, AC	121	109	11	31	Base Metal	-	40
GMA	Production Heat	Ti-621 0.5	0.062	As-Welded	120	108[b]	10	31	Base Metal	39	41
	Production Heat	Ti-621 0.5	0.062	900 F, 2 hr, AC	127	113[b]	9	26	Base Metal	35	39
	Production Heat	Ti-621 0.5	0.062	As-Welded	125	113[c]	12	23	Weld	10[d]	-
	Production Heat	Ti-621 0.5	0.062	900 F, 3 hr, AC	127	116[c]	11	25	Weld	38[d]	-

Note: Represented are a pilot heat of 100 lbs rolled to 1-inch plate, and two 30-inch diameter, 7000-lb production heats, No. 292555 rolled to 1-inch plate and No. 292596 rolled to $2\frac{1}{2}$- and 1-inch plates.

[a] NRL has evaluated the weld toughness of other Ti-621 0.8 GMA welds. In the as-welded condition the drop weight tear test was 2206 ft-lb and in the as-welded beta anneal with helium cool the drop weight tear test was 2560 ft-lb.

[b] Yield strength of weld was determined using SR-4 strain gauges mounted on the weld zone of the tension specimen.

[c] These data were determined from "all-weld" specimens.

[d] The Charpy V-notch impact strength of the weld zone at -80 F is 35 ft-lb for both the as-welded and stress relieved (900 F - 3 hr -AC) conditions.

TABLE 16 Fracture Toughness for Ti-100 Weldments. Oxygen Content of Base Metal -0.054 Weight Percent[36]

Filler Metal	Welding Process	Specimen Type	Condition	Yield Strength ksi	Stress Corrosion Threshold Values 1-Hour Tests, B-1.375 in.* K_I air	K_I seawater	$K_{I\,sw}/K_{I\,air}$
None		Base	As Received	108	123	120	0.98
Ti-6Al-2Cb-1Ta-0.8Mo [0.054(O)]	GTA (manual)	Weld	As Welded	112		110	
Ti-6Al-2Cb-1Ta [0.080(O)]	GMA (semi-automatic short arc)	Weld	As Welded	105		75[a]	
Ti-6Al-2Cb-1Ta [0.080(O)]	GMA (semi-automatic short arc)	Weld	Stress Relieved			61[a]	

Note: The data represent single test determination. Fracture toughness determined using cantilever beam notched bar specimens.

[a]These K_I values fulfill the requirements of the relationship $B > 2.5(K_Q/YS)^2$, where B is the thickness of the specimen.

*Tests for threshold values normally require periods of thousands of hours to obtain reliable results.

VI. USE CONSIDERATIONS

A. INTRODUCTION

Welded structures fabricated from high-strength materials such as HY-180 and Ti-100 can be separated into two classes:

1. Structures for which a rigorously correct stress analysis can be performed by either analytical or experimental techniques at all locations. Such structures are characterized by geometric simplicity and performance requirements that justify the most exacting attention to fabrication and quality assurance techniques. Rocket cases, aircraft components, and certain components of high-performance surface ships fall in this class.
2. Structures for which, by virtue of size and/or geometric complexity, an exact stress analysis is impossible. In such structures, the inherent plasticity of the structural material must be adequate to allow redistribution of the load at geometric features and flaws which cause localized stress concentrations. Thick-walled pressure vessels (containing nozzles, manholes, and changes in wall thickness), armored vehicles, and both surface and undersea combat ships fall in this class.

To be serviceable, a structure in either class must be of fracture-safe design whether the criterion be based upon fail-safe or safe-life design concepts.

B. USE CONSIDERATIONS AT AMBIENT ATMOSPHERIC TEMPERATURES AND IN BENIGN ENVIRONMENTS

1. The high-performance requirements imposed upon Class 1 structures mentioned above generally render cost considerations secondary in importance. Thus, the designer can employ instrumented sub-scale models, photoelastic studies, and complex computerized stress analysis techniques to verify the design. The individual components can be machined to precise tolerances and elaborate fixturing can be justified to position and align the components for joining. The

optimum choice of welding process and procedures can be justified regardless of capital cost or deposition rate, providing both the size and incidence of flaws and the extent of metallurgical damage in the heat-affected zone are minimized. Finally, the most exacting and sophisticated techniques of nondestructive evaluation (NDE) can be employed in order to assure that all flaws of critical size are detected and eliminated by proper repair procedures. In fact, recent developments in stress wave analytical techniques (SWAT--also called acoustic emission) permit detection and location of slow-growing flaws during proof testing so that repair of potentially dangerous defects is possible even if they are below the level of detection by more conventional NDE techniques.

In summary, if cost is of secondary importance, there are no insurmountable obstacles to the fabrication of fracture-safe welded Class 1 structures from either HY-180 or Ti-100. The potential problems are service related and involve the effects of environment and loading conditions on the rate of growth of existing subcritical flaws. Since these problems are common to both classes of structures, environmental and loading considerations will be summarized below.

2. Since many regions of Class 2 welded structures (see previous page) are what Pellini calls "stress-indeterminate,"[3] the accuracy of computational stress analyses for even the nearby regions of relatively simple geometry may be unacceptably low. Therefore, it is essential that the material possess sufficient fracture toughness to assure one of the following:

   a. Existing flaws experiencing slow growth are arrested before reaching critical size.

   b. Existing flaws experiencing slow growth can be detected and removed and repairs made before the flaw reaches critical size.

c. The growth rate of existing subcritical flaws is so slow that no flaws reach critical size within the design life of the structure.

If a design is to be fracture-safe, the material used must possess a minimum level of fracture resistance appropriate to the particular structural problem. In terms of the location of the material on the RAD, materials for use in Class 2 structures should be located within the plastic region (i.e. above and to the left of the $K_{Ic}/\sigma_{ys} = 1.0$ line) if yield strength stresses (σ_{ys}) are likely to be encountered. It is important to note that since residual stresses in welds approach yield stress magnitude in both the longitudinal and transverse directions the superposition of even minor service loads will cause yield strength stresses or greater to be present in the vicinity of welds.

Thus, as noted earlier, to assure that a welded Class 2 structure will be fracture-safe, the statistical expectancy box for the material in the thickness used must fall above and to the left of the line for $K_{Ic}/\sigma_{ys} = 1.0$ on the RAD. Figure 3, prepared for 1-inch plate, indicates that the only data available for HY-180 steel at the time meet this requirement in the absence of any adverse environmental influences. Similarly, Figure 4 indicates that both plate and weld metal for the Ti-100 system are well within the required limits. To date, no published data for welds in the HY-180 system are available so additional work is required to locate the weld metals deposited by various processes on the RAD.

It should be emphasized that the statistical expectancy boxes in both diagrams are based on a limited number of heats of material, few of which were of commercial size. Thus, the quality is estimated to be within the "high" corridor for HY-180 and the "intermediate to high" corridor for Ti-100. However, before these materials can be used with confidence additional data from several production-size heats must be obtained to establish reliable bounds for the "statistical expectancy boxes" of both materials.

C. USE CONSIDERATIONS RELATED TO ENVIRONMENTAL CONDITIONS

1. Temperature Effects

In general, fracture toughness increases as service temperature is increased and decreases as service temperature falls below ambient. This characteristic has the effect of moving the statistical expectancy box downward and to the right for service temperatures below ambient atmospheric levels. The lower regions of the expectancy box for HY-180 occur only slightly above the $K_{Ic}/\sigma_{ys} = 1.0$ line (Figure 3), implying that some lots of HY-180 might exhibit elastic-plastic fracture states at low service temperatures. This possibility should be carefully explored before utilizing this material at service temperatures below room temperature.

Provided the service temperatures are not high enough to cause softening and reduction in yield strength, service at temperatures above ambient atmospheric levels in benign environments should constitute no problem for HY-180 steels.

High-strength titanium alloys exhibit only a slight decrease in fracture resistance with decrease in temperature. Thus, the sensitivity of Ti-100 to service temperatures below ambient atmospheric should be small. The possibility that service temperatures above ambient might increase the creep rate observed at ambient temperature should, however, be investigated further for Ti-100.

2. Active Environments

The ability of high-strength structures welded from HY-180 and Ti-100 to serve in environments with which they experience electrochemical interaction can by limited by:

a. General corrosion

b. Pitting corrosion

c. Stress-corrosion cracking

d. Corrosion fatigue

Insufficient data are currently available on the influence of various environments on these phenomena. Recent work reported by Pellini* indicates that HY-130 experiences a significant increase in crack growth rate when the material is made cathodic in seawater. If made sufficiently cathodic, the fracture state shifts from high level elastic-plastic to plane strain fracture. Thus, the effect of electrochemical potential on crack growth rate both during stress-corrosion cracking tests and corrosion fatigue tests must be studied before HY-180 can be utilized in critical structures with confidence. Furthermore, tests of weldments should be performed to determine if the difference between the chemical compositions of the weld metal and base metal has a detrimental influence on K_{Iscc}.

D. USE CONSIDERATIONS RELATED TO LOADING CONDITIONS

1. Static Loading

The RAD data for both candidate materials indicate that fracture-safe structures could be produced by currently available techniques. However, cost-effective fabrication of Class 2 structures will be possible only if designers can be trained to:

a. Shift welds out of highly stressed locations into non-critical regions of the structure

b. Make weld joints readily accessible, from both sides wherever possible, to facilitate both welding and NDE of the weldments

c. Eliminate "T" joints by using "T" shaped forgings butt welded to the legs of the "T"

* Welding Workshop ONR, Washington, D.C., 1/24/74

d. Design the structure to make possible the maximum utilization of mechanized welding

e. Minimize the volume of weld metal required in the joint.

Obviously, the above concepts are equally pertinent to all forms of loading and will therefore not be repeated in the following sections.

2. Cyclic Loading

The studies performed thus far are insufficient to characterize all aspects of the fatigue behavior of HY-180 steel. They do, however, confirm that HY-180 steel behavior is similar to that which would have been predicted on the basis of previous studies of the lower strength HY-steels, i.e., that any superiority in fatigue behavior for HY-180 steel can only be realized in the smooth, polished condition. In the presence of stress raisers such as mechanical notches and undercuts due to welding, the HY-180 steels fall into the same general scatter band of the other steels.

References 1, 37, and 38 summarize the fatigue data available on HY-180 steel thru June 20, 1972. Because of the deemphasis placed on the HY-180 steel development in 1972, little additional fatigue work has been done.

Since many design criteria permit cyclic loading to 75 percent of the yield strength, the number of cycles from zero-stress to this stress level required to cause a flaw of a given initial dimension to grow to a specified depth often is employed as a means of evaluating the resistance to failure in low cycle fatigue.

Figure 16 relates the flaw depth in inches to the number of cycles from 0 psi to $0.75\sigma_{ys}$ for HY-80, HY-130, HY-180, Ti-100, Ti-120, Ti-150, and Ti-180 in 5.0-inch thick specimens precracked to produce a 0.5 inch long flaw 0.05-inch deep and tested in salt water.

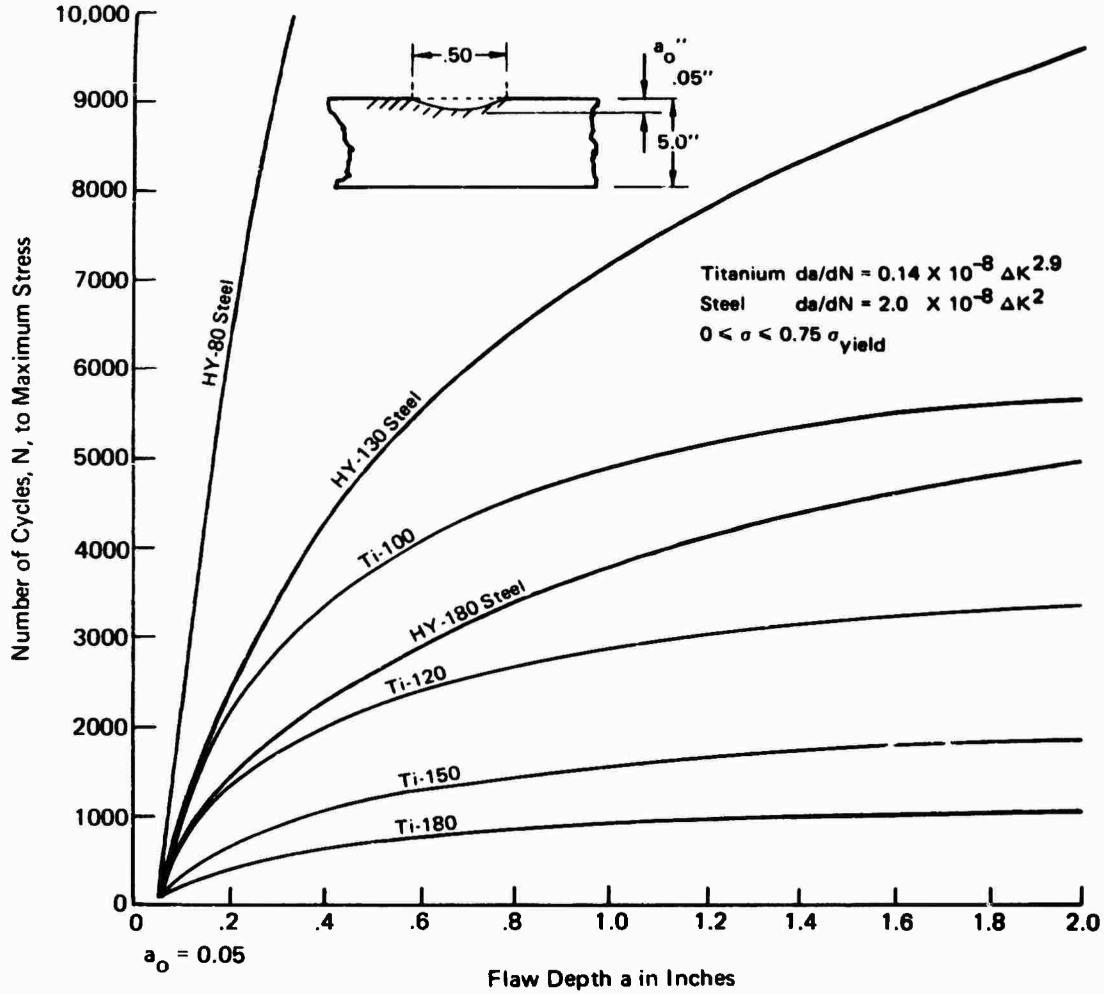


FIGURE 16 Flaw growth rates for high strength metallics in salt water. (Test frequency typically 6-60 cyles/minute).[17]

It is of interest to note that after 2,000 cycles, the crack depth in HY-130 and Ti-100 was nearly double that of HY-80, but only slightly over one-half that of HY-180 and Ti-120, when cyclically loaded at the same fraction of their respective yield strengths.

It should be emphasized that all research conducted on welded structures indicates that the endurance limit is independent of the yield strength of the base material. Therefore, if fatigue life or fatique strength is the limiting feature of the design of a welded structure there is no justification for the use of HY-180 or Ti-100.

3. Impact Loading

Additional engineering data on the resistance of both HY-180 and Ti-100 weldments to impact type loading should be generated. Explosion bulge data would be helpful in evaluating this important characteristic. The data presently available are too limited to permit adequate characterization of this important behavior.

VII. CONCLUSIONS

1. For the overall performance desired, only HY-180 (10Ni-8Co-2Cr-1Mo steel) and Ti-100 (Ti-6Al-2Cb-1Ta-0.8 Mo) are considered to be suitable candidate materials at present.

2. Both HY-180 and Ti-100 can be produced in commercial sizes and in most commercial forms although additional work is required before castings with acceptable properties can be obtained in either alloy.

3. Vacuum-arc-remelted HY-180 is qualified for applications requiring toughness such as $(K_{Ic}/\sigma_{ys})^2 = 1.0$ at a yield strength level of 180 ksi.

4. Ti-100 is qualified for applications requiring toughness such that $(K_{Ic}/\sigma_{ys})^2 = 1.0$ at a yield strength level of 100 ksi.

5. Both HY-180 and Ti-100 can be used to fabricate components in sections thin enough to be welded with the gas tungsten arc process. Both the process and the currently available filler metals are sufficiently reliable to be used to fabricate a properly designed structure from these materials with confidence.

6. Considerable progress has been made in producing satisfactory weldments in HY-180 steel at deposition rates of 10 lb/hr. Weldments made under laboratory conditions with both hot-wire GTA and hot-wire plasma-arc processes exhibit high elastic-plastic and fully plastic DT behavior in 1- and 2-in. sections, but additional work will be required to accomplish this either out-of-position or under shop conditions.

7. Ti-100 can be electron beam welded readily in chamber, but the stray magnetic fields common in high strength steels make the precise control of the beam required for seam tracking difficult in HY-180 structures.

8. The probability of developing covered electrodes for joining either HY-180 or Ti-100 is remote. Therefore, most welded structures must

be designed to be fabricated with inert-gas-shielded welding processes, or other non-contaminating processes, and suitably small and versatile welding equipment must be designed to function properly in confined locations.

9. Conventional GMA welding with either argon or argon-helium mixtures can be used to fabricate Ti-100. Although the argon-oxygen mixtures required for conventional GMA welding of HY-180 cause an intolerable loss in weld metal toughness, GMA helium and GMA argon with treated wires show promise of producing welds of acceptable quality.

10. Pulsed GMA with pure argon shows promise for out of position welding of Ti-100, but the argon-oxygen mixture required to stabilize the arc when welding HY-180 embrittles the weld metal.

11. The utilization of either candidate material in fracture-safe structures requires that the statistical expectancy box for the material in the thickness used fall above and to the left of the line for $K_{Ic}/\sigma_{ys} = 1.0$ on the Ratio Analysis Diagram. Before a reliable characterization of the statistical expectancy box on the RAD can be established for either material, testing of several more commercial-size heats will be required.

12. The aerospace industry has developed and consistently applies welding and inspection procedures adequate for fabrication of reliable structures from either alloy. However, in view of the current process limitations and the unlikelihood of developing acceptable covered electrodes for either alloy, successful fabrication of either alloy in ship yards and ordinary production facilities will require revolutionary changes in both the design and welding procedures employed. In addition, it is certain that unless the more rigorous and expensive quality assurance procedures developed by the aerospace industries are adopted as well, it would be unwise to fabricate complex or critical structures from either alloy in either shipyards or ordinary production facilities.

13. It should be emphasized that all research conducted on welded structures indicates that endurance limit is independent of the yield strength of the base material. Therefore, if fatigue life or fatigue strength is the limiting feature of the design of a welded structure there is no justification for the use of HY-180 or Ti-100.

VIII. RECOMMENDATIONS

A. MATERIAL CONSIDERATIONS

1. Additional commercial-size production heats should be made and tested to establish reliable bounds for the statistical expectancy boxes for both candidate materials on the appropriate Ratio Analysis Diagram and to investigate the influence of production variables on fracture toughness.

2. Melting, pouring, and processing parameters should be developed for obtaining optimum properties in plate of various thicknesses up to 8-inches thick, including the determination of optimum ingot size for both materials.

3. The newer melting practices such as electroslag remelt, electron beam melting, and plasma arc remelt should be studied to determine whether they significantly improve the fracture toughness of the candidate materials.

4. The effect of potential service environments on general corrosion, pitting corrosion, and (probably most important) stress corrosion of both candidate materials should be studied.

5. The effects of dynamic loading on the fracture toughness of both materials should be studied. The effects of both strain rate and cyclic loading (including low-cycle fatigue and random fatigue loading) on the rate of crack growth should be studied both in air and in potential service environments.

6. Techniques should be developed to produce castings with adequate fracture toughness to be incorporated in fracture safe designs.

7. The feasibility of commercial production of titanium by electrolytic reduction to obtain lower contents of the detrimental elements oxygen and iron should be assessed.

8. The specific heat, thermal conductivity, and electrical resistivity of Ti-100 should be determined.

MATERIAL CONSIDERATIONS - Cont'd.

9. The influence of cold forming on fracture toughness should be studied and it should be determined whether either strain hardening or strain aging impair the fracture toughness of the candidate materials.

10. If cold forming proves injurious to fracture toughness, heat treatments or alternate forming procedures should be developed to eliminate the problem.

B. WELDING PROCESSES

1. Studies should be initiated immediately to develop procedures that can be employed to replace shielded metal arc welding for all-position welding since it is unlikely that covered electrodes will be developed for either alloy system.

2. Research should be stimulated to develop oxygen-free gas metal arc welding processes for HY-180. Both emissively coated wires and GMA-Helium show promise but both require further development.

3. Programs for scaling up the plasma-arc welding process should be conducted to provide thicker penetrations in the key-hole mode in both alloy systems.

4. Filler alloys that are tolerant of higher energy input than those existing now should be developed.

5. The effect of welding thermal cycles on the mechanical properties and fracture toughness of the various regions of the weld heat-affected zone in both candidate materials should be determined.

6. Detailed studies should be made to develop weld repair procedures that will not induce new defects of a macro or micro nature in the repair zones. A process and procedure should be qualified for each type of

original weld because of the differences in thermal shock and metallurgical changes developed in the welded zones and the adjacent plates.

7. Methods for welding Ti-100 castings should be developed and their effects on properties determined.
8. Methods for joining Ti-100 to other titanium alloys and to other alloys, both ferrous and non-ferrous, should be developed.
9. Allowable levels of weld imperfections should be determined and accept-reject criteria established for weldments in both candidate materials.
10. A non-destructive method for determining the interstitial content of titanium welds (preferably of the entire weld rather than just a discrete area) should be developed.
11. The amount of contamination that can be tolerated should be determined for both materials and specifications for filler metal and base metal cleanliness should be established based on such findings.
12. Standards should be developed for measuring cleanliness of filler wires.
13. Practical methods should be developed for preweld cleaning and inspection.
14. Means should be developed for monitoring shielding gas atmosphere in order to prevent weld defects resulting from impurities in the gas envelope.
15. Improved stress relief techniques should be developed for Ti-100. Present methods relieve stresses but may have adverse effects on the mechanical properties of the welded joints.

C. WELDMENT PROPERTIES

1. The influence of energy input, preheat and interpass temperature, and chemical composition of the filler metal on the fracture toughness of weldments in both candidate materials should be determined for each of the welding processes to be used.
2. The sensitivity of HY-180 weldments to hydrogen-induced cracking should be investigated.

D. QUALITY ASSURANCE

1. The sensitivity of existing techniques for non-destructive evaluation of weldments (when properly applied) appears to be adequate for complex structures fabricated from HY-80 and marginal for those fabricated from HY-130; however, more sensitive NDE techniques should be developed to insure that welded structures fabricated from either HY-180 or Ti-100 are fracture safe.

2. To assure that proper welding procedures are employed in welding either HY-80 or Ti-100, in-process inspection procedures should be developed that are much more rigorous than those currently used in any industry except the aerospace industry. This will probably necessitate the training of "welding observers" who will represent the quality assurance department on the fabrication line and actually observe whether the specified welding procedures are rigorously followed at all times by the weldors.

E. DESIGN CONSIDERATIONS

1. New design techniques should be developed for structures to be welded from either HY-180 or Ti-100. These techniques should include:
   a. Shifting welds out of highly stressed locations into noncritical regions of the structure
   b. Making weld joints readily accessible, from both sides where possible, to facilitate both welding and NDE
   c. Eliminating "T" joints by using "T" shaped forgings to replace the fillet welds in critical areas of the structure by butt welds located in noncritical regions
   d. Designing the structure to make maximum use of automated and mechanized welding procedures
   e. Minimizing the volume of weld metal required in the weld joints

2. Practicing designers should be trained in these techniques and in the absolute necessity of utilizing them.

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